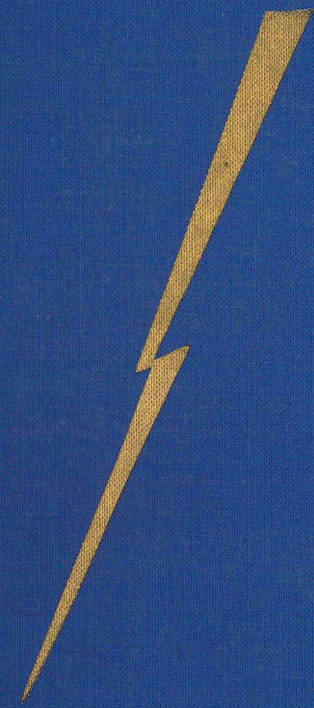
McEACHRON

PATRICK

PLAYING WITH LIGHTNING

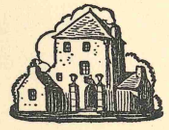
RANDOM HOUSE



PLAYING WITH LIGHTNING

PLAYING WITH
LIGHTNING

By DR. K. B. McEACHRON
in collaboration with
KENNETH G. PATRICK



RANDOM HOUSE · NEW YORK

FIRST PRINTING

PRINTED IN U. S. A.

COPYRIGHT 1940 BY RANDOM HOUSE, INC.

CONTENTS

1. FEAR AND DISCONTENT 3
2. THE THUNDERER 10
3. FRANKLIN PLAYED WITH FIRE 23
4. DAMAGE AND DEFENSE 33
5. HOW MUCH? HOW FAST? HOW LONG? 43
6. MEN MAKE LIGHTNING 48
7. HOW QUICK IS A FLASH? 63
8. GHOSTLY ARITHMETIC 79
9. HITS AND MISSES 90
10. INDOOR THUNDERBOLTS 103
11. GUNPOWDER OF THE GODS 112
12. DISSECTING THE LIGHTNING STROKE 122
13. SKYSCRAPER FIREWORKS 135

14. FREEZING LIGHTNING ON FILM 152
15. THE THUNDERSTORM 171
16. FOLLOW THE LEADER: SOME CASE-HISTORIES 183
17. LIGHTNING RODS 200
18. SHAKE HANDS WITH LIGHTNING 211

ILLUSTRATIONS

FACING PAGE

The home of Julius Saxton, White Plains, N. Y., following a lightning stroke 8
Twenty-two cows killed during a lightning storm in Montoursville, Pa. 9
A strain-tower of the Hoover Dam-Los Angeles line 24
Edison and Steinmetz examining an insulator 25
A time exposure of a 1,000,000-volt three-phase arc 104
Laboratory lightning striking a miniature lightning rod 105
What happened to a No. 25 nichrome wire when 5,000,000 volts passed through it 120
Lightning striking a New Jersey beach 121
A Fulgurite made in the High-Voltage Laboratory at Pittsfield 140
The antenna system atop the Empire State Building 141

ILLUSTRATIONS

	FACING PAGE
Still- and moving-lens photographs of stroke No. 13	160
Stroke No. 16, taken in August, 1937	160
High-speed Boys camera photographs of stroke No. 16	161
A long-continuing upward leader stroke showing upward branching	161
A continuing flash of lightning taken in Switzerland	186
A stroke to a 60-foot pine tree	187

PLAYING WITH LIGHTNING

1. FEAR AND DISCONTENT

IF YOU heard the thunder, the lightning did not strike you. If you saw the lightning, it missed you; and if it did strike you, you would not have known it.

There is a strange combination of fatalism and comfort in those words, but they represent much that the average human being wants to know about lightning. For as he returns to his window and cocks a weather eye at the horizon, white flame shoots across the skies, there is a ripping, tearing sound not too far away, climaxed by an ear-splitting crash—and the same human being finds that words, no matter how comforting or authoritative, are poor protection against nature's awesome and savage demonstration.

"How do you *know* I'm safe?" he asks, and "What

is lightning? Where does it come from? What can I *do* about it? Why should anybody want to study lightning? Why, I knew a chap once who . . ."

Lightning runs neck and neck with ghostly bodies as the inspiration of the story-teller. But unlike those tales in which the villain of the piece is a sheeted spirit, most of the lightning stories are true. At least they are as true as an astonished and imaginative narrator can recall them. There was the 7-year-old boy sitting in his cart underneath a 40-foot tree. Lightning shattered the tree throwing pieces 70 yards and removing three sides of the boy's cart, but the boy was not hurt. There was the bolt that ignited a building and then struck a fire-alarm box near by, providentially bringing the firemen to the scene with dispatch. There was the well which ran dry after lightning struck a near-by tree, and the case of the kindling, laid in preparation for the next morning, which was fired by lightning. Documented stories, all of them. A careful reading of the newspapers during the next sultry season will turn up even more evidence of the pranks and tragedies caused by lightning.

The tales will go on, repeating themselves in cycles just as folk tales do, for lightning is ageless and elemental. Because it is ageless, there is no beginning to which the scientist can go back in founding his research. And because it is elemental, there will never be anything that he, or any other man, can do to prevent its erratic

and uncharted recurrence. *Donner und Blitzen* will be always with us, but we need not always stand by the window helplessly, or hide our head under the blanket, while it plays havoc with power lines, fires buildings, destroys forests, and takes human lives.

Disaster is a distinctly human by-product. In a world without life it would not exist any more than would a loud noise, a bad odor, or a brilliant color. It is a word we have coined to represent the shocks occurring to our senses, a word which has had in its implications a tremendous effect upon our progress. Although lightning is ageless, it has written its own story in human terms, and there is some modest cause to think that in doing so it has begun to shackle itself. Yesterday, we watched the lightning and heard the thunder. Today, we are following its steps slowly and studying its progress painfully. Tomorrow, we may be able to build an ingenious fence around our person and our property and defy in some measure another destructive force.

This may seem rather grandiose and overconfident language for mere mortals, yet man has conquered the land and the sea, and even the air. It should not be implied that the men who work with lightning take their adversary lightly, for they do not. They have an infinite respect for his volts and amperes. Electricity, either man-made or heaven-sent, is still the great unknown. It will never be conquered by adjectives, and such advantage as we now enjoy was gained by curi-

osity and unremitting, unspectacular hard work. The actual tools are most likely to be mathematics, physics, and chemistry. If we occasionally indulge in the luxury of a high-flown challenge in the direction of Jove, or make as if to pat lightning familiarly on the back, it may be set down as harmless posturing, for tomorrow we will be back in the laboratory, flipping switches and making notes.

Lightning's history, then, is entirely man-made. It begins with fear and is fed by discontent. Our bearded ancestor, crouching in a cave, watched the flashes with a mixture of fascination and fear. As thunder disturbed his peace and lightning brought tall trees down about his ears, he resented its arrogance and was discontented with his own impotence. Modern sentiments are similar, modern impotence not so great, modern curiosity a fitful flame that feeds our striving. Most important of all, scientific methods have taught us patience.

We have learned a little. Today we know some of lightning's habits. We have an intelligent appraisal of its strength. We have even learned to produce its artificial equivalent in the laboratory. We have learned much about how to protect ourselves and our property as our knowledge has grown. Lightning, this commodity that we are manufacturing in small amounts, is a product without a market. Like war, its sole value lies in its prevention.

In spite of the aforementioned fascination-fear char-

acteristic of lightning, there is only one practical reason for studying it, and that is to protect lives and property. This is a study requiring considerable time and money, and it is an undertaking, therefore, that has had to be liberally financed. The support has come from those with the largest immediate stake, in typically American fashion—manufacturers of electrical equipment for transmission of electrical power and for communication, also electrical utility companies, to whom the ravages of lightning mean interrupted service to customers and capital loss to investors.

Any broad-gauge scientific achievement is usually the result of the efforts of many men and many agencies, and lightning study is no exception to the rule. The following pages represent no complete and all-inclusive account of the work that has been done, nor do they seek to distribute credit fully where it belongs. No one can foresee when the last word on the subject will be written, nor even desire that it should be written, for it is a long story and not one to be hemmed in by false limits.

This is only a record of what a handful of men have discovered in their pursuit of a flash of flame and a roll of thunder across the sky. Most of them have been associated with the high-voltage laboratories of the General Electric Company. To support the findings and give them their proper position in the whole picture, it is only fair to say that in the light of present knowl-

edge, this work, extending over a period of several years and still being actively carried forward, is believed to be the most comprehensive study of the subject now in progress anywhere in the world.

So fast does the modern world move that already men like Steinmetz are history, their far-reaching achievements acquiring new luster as theory becomes practice and realization of the social benefits grows. No study of lightning could properly begin, however, without at least a hurried glance backward—perhaps not without a nod in the direction of Benjamin Franklin himself. After that we may attempt to describe lightning, how it forms, how fast it moves, where it is likely to strike, what may happen, and what can be done about it.

At the time the first serious campaign was begun to record and measure lightning, the men assigned to this duty had to accustom themselves to a rather unusual routine. Midsummer is the thunderstorm season, and lightning flashes can be recorded by camera only at night. It often seemed as though electrical storms took a puckish delight in occurring in the hours after midnight, just as the observers were settling into sleep. At the first storm warning, they would arise from their beds, throw on clothes, and hasten to the appointed place of study. If all went as indicated in the heavens, a thunderstorm would follow. One of our engineers had a small daughter, then about five years old, who

The home of Julius Saxton, White Plains, New York, following a lightning stroke during a storm on June 21, 1936.

Twenty-two cows killed during lightning storm in Montoursville, Pa. Note path of stroke down tree in left foreground. Courtesy of *Grit*.

eventually came to confuse cause and effect, after watching her sleepy parent's departure on numerous occasions. She was convinced that daddy went to the plant and "turned it on," and after several minutes of the storm had brought her to the required pitch of excitement, she would beseech her mother to "ask daddy to turn it off."

The child has many counterparts in the adult population. Impelled by the same desire to have someone "turn it off," they may find more than a passing interest in this account of our efforts to do substantially that, as far as its effects upon man's activities are concerned.

2. THE THUNDERER

LIGHTNING, striking with a roar and a blinding flash, uprooting trees and fusing metal, bringing destruction and even death in its wake, has enjoyed a commanding and fearsome stature in the sight of men since the beginning of time. Depending upon our degree of culture and understanding, and even more upon our sensibility to the message of titanic forces, it has brooked no rivals as heaven-sent bogey man No. 1. There is about thunder a strong suggestion of the day of wrath, and perhaps that should be accounted one of its benefits down through the ages—that it can so quickly and completely induce in careless mortals a sudden and perhaps forgotten respect for the Creator of the Universe. A man's conscience, which may have

become too still and too small in daily practice, often assumes stentorian tones with the aid of thunder and lightning.

Those who have consistently been thus humbled by the majesty of the elements should derive a warm, compensating satisfaction from the life of Charles Proteus Steinmetz. A dwarf, little more than four feet tall, with a sadly crippled body, he crossed lightning's path, not with an angry fist, but with an amazing brain. This was certainly not the greatest achievement of his brief but fruitful life. Perhaps it was the most colorful. From a public just awakening to scientific interest he won the name of "The Thunderer," a sobriquet which better reflected his problem than his method. For Steinmetz was a quiet, kindly man who had but a single adversary—the unknown. His weapons were for the most part mathematical, but their significant influence in lightening the world's tasks has not even yet been exhausted.

Born in Breslau, Germany, in 1865, he was a pupil, at 14 years of age, of the philosopher Fechner, who never took anything for granted and imparted that valuable method of study to his young charge. There is about Steinmetz's early years in Germany a curious parallel to the experiences of many modern scholars. He entered the University of Breslau in 1882 and pursued his studies and intellectual pastimes in the spreading shadow of Bismarck. In his senior year he was forced to flee to Switzerland to escape political imprisonment,

and studied for a year at the Zurich Polytechnical School. At the insistence of a friend in similar straits, he sailed for America, arriving one morning at Castle Garden without knowledge of the English language, with no visible means of sustenance, and with a bad cold which had caused his face to swell and added little to his already unprepossessing appearance. The immigration officials decided to refuse him entry without further ado, and only when the friend came to his rescue and promised to look after him did they change their minds.

As often seems to be the case in scientific investigations extending over a period of many years, there is no sharp line of demarcation between the different subjects an individual studies; his problems—and most of them are never conclusively solved—are not done up in neat little packages, labeled, and put upon a shelf, but have an annoying and fascinating way of becoming inextricably tangled up with each other. No one knows where the ramifications may lead. Edison set out to remove the discoloration from his new-fangled incandescent lamp, and accidentally discovered something which later turned out to be the radio industry. Dr. Willis R. Whitney, experimenting with fruit flies and high-frequency currents in his Schenectady laboratory, noted that his associates developed consistent headaches and slight nausea, and because his curiosity was aroused, he evolved the artificial-fever machine and advanced

the science of fever-therapy. Strange patterns come off the loom of research, but the fabric is always closely and carefully knit nevertheless.

So it was with Steinmetz and the 34 years of his life in America. Certain phases of his continuous investigation, however, serve as definitive guide-posts along the way. These were three in number—magnetism, the mathematics of alternating current, and transients. To the layman they sound downright dull, but nothing could be farther from the truth. Three and a half years after Steinmetz had come within an eyelash of being barred at Castle Garden as an undesirable alien he had established himself before the scientific world as a new and powerful thinker, through the announcement of his law of hysteresis and his development of alternating-current formulas. Neither achievement was of the kind understood by ordinary men, yet they constituted the tools which others would use to carve out many of the wonders of the electrical age.

It was after Steinmetz moved to Schenectady in 1893 that he began his study of transients. Since that study most concerns what is to follow, this is a good point at which to begin definitions. Transient electric currents, as the name implies, are those which suddenly and unexpectedly enter an electrical system, because of a disturbance such as a short circuit, or because of lightning. A transient current is something like a tramp who wanders into a farmyard, arouses the dog, calls

the wife away from her cooking, causing the pot to boil over, and in general creates a disturbance without profit. The tramp can't be prevented, but he may be guarded against. It was this study which eventually led Steinmetz to create artificial lightning. In effect, he already owned a convenient farmyard so he proceeded to invent an artificial tramp whose habits he could control and study.

Lightning research, being an infant in years, is graced by few historical monuments, but one exists today in Henry Ford's famous restored area of Americana at Dearborn, Michigan. It is a little one-room wooden shack, first erected on the banks of the Mohawk River near Schenectady, later taken apart piece by piece and reassembled on the River Rouge in Greenfield Village. It was this camp which was Dr. Steinmetz's play spot, built by him, and definitely a part of his way of life. In it he wrote the electrical textbooks which came to be recognized as fundamental by engineers. Fortunately, Steinmetz was not in it during the summer of 1920 when it was struck by a bolt of lightning.

The pleasant location of the camp was discovered accidentally one afternoon while Steinmetz was canoeing with some companions, and within a few years he had built a lodge of a single room, about 25 feet square, perched precariously among the trees and supported on the river side by several slender two-by-fours. Its appearance was none too reassuring. Always the man of

science, the Doctor devised an original test for stresses and strains. He held a house-warming at the camp and hired a German band of a few pieces to entertain the guests. The musicians were stationed on the far side of the room, over the slender braces, and they played merrily throughout the evening, unaware of the role they were fulfilling or of their possible fate should the test prove a failure.

On an August afternoon in 1920 Steinmetz and his laboratory assistant, Emil Remscheid, had planned to forsake Schenectady for the cooler river camp, but a swift-gathering storm and torrential rain spoiled their plans and in all probability saved the lives of one or both. For lightning struck the camp—struck, in fact, the table where the Doctor customarily worked or watched storms. It was the "isolated instance" so valued by scientists, for the bolt left behind it exactly the sort of data he desired. A tree was splintered, two-by-four planks were smashed, wires were fused, lights burned out, and a mirror broken into fragments. The accident had occurred on his own property, where no one could tamper with the evidence. Steinmetz went over the ground as would a Sherlock Holmes on the scene of a celebrated crime, taking careful notes of the path followed by the lightning.

The bolt had first struck the gnarled "snake tree" a foot away from a window, then it broke the window, leaping inside. There it splintered his work table,

jumped to the far side of the camp, and shattered a bedroom mirror. The Doctor ordered Emil to collect all the pieces of broken mirror, fit them together in a box cover, and take them back to town. These fragments were later assembled between two sheets of glass, so that the pattern struck off by the lightning charge could be studied. They constituted perhaps the first "portrait" ever preserved of lightning's effect.

Steinmetz's interest in lightning was a gradual growth induced by related problems which antedated the accident at the camp. He had early been interested in the problems of transmitting and distributing electric current, when the highest transmission voltages known were 7000 volts. As the distance of transmission increased, the voltage was increased in the interests of economy. The size of the copper conductors, or wires, carrying this current was of extreme importance, since at high electrical pressures, or voltages, current would leak from the cable if too small in diameter, creating the effect known as corona loss—visibly glowing sparks or streamers which indicated escaping current.

Steinmetz decided that before good lightning arresters could be built to protect electrical apparatus, it would be necessary to study lightning itself—its causes, how it behaved, and how much energy it might contain. Lightning arresters are the watchdogs of the transmission systems which span the country (Steinmetz called them traffic officers) while lightning was the hit-

and-run driver. It was upon this more or less theoretical scene that the accident of 1920 broke, inspiring the construction of the first high-voltage lightning generator, laboratory style.

Dr. Steinmetz was fond of remarking that when an actual lightning bolt strikes some place upon the earth, no one is able to see just what happens.* In general, no one knows when or where it will hit. Up to this time it had been impossible to obtain that precise information so much needed to increase human knowledge. In 1921 he decided to build his first lightning generator so that he could watch lightning strike. A few years before, there had been developed in the laboratory a type of vacuum tube called the kenotron, which made it possible to change high-voltage alternating current to direct current similar to that identified as typical of the lightning stroke.

Steinmetz followed nature in producing his lightning. A thundercloud is made up of countless raindrops which in sultry weather have formed in space. Each drop or particle has accumulated a small charge of electricity (some are charged positively and some negatively) and these drops, while making up what we know as a cloud, are insulated from each other by air. In the thundercloud we might say that two kinds of action take place, physical and electrical. In the physical action

* In 1934, a photograph of lightning striking a beach was taken from a point 100 feet away. It is reproduced to face page 121.

the small drops join together to become larger drops, until their very weight causes them to fall toward the earth. Action of the air upon them, as they fall, causes them to break apart, and the smaller drops are forced upward again by air currents. While this is happening, the electrical action takes place, due partly to the breaking of the drops, partly to polarization of the drops by induction, and partly to the well-known fact that electrical charges of like sign repel each other, while those of opposite sign attract each other. The earth, of course, has its own quota of positive and negative charges. For a reason which need not be discussed at this point, the negative and positive charges in the cloud sort themselves out in such a manner as to cause the negatively charged particles to concentrate in the lower portion of the cloud, while, in general, the positively charged particles seek the upper portion. The concentration of negative charges in the bottom of the cloud attracts and controls a similar concentration of positive charges in the earth below, at the same time causing the earth's negative charges to flee that particular area.

As the electrifying process continues—drops falling, breaking, and being carried up again—the charges accumulate, finally becoming so intense as to start the discharge which we know as lightning; the electrical stress between the cloud and the earth having become so great that the insulating character of the air breaks down entirely.

Steinmetz calculated that a natural bolt of lightning discharges at a pressure of 100,000,000 volts, and he estimated its power at about 500,000,000 horsepower. The first artificial generator he built had a potential of 120,000 volts and power of 1,000,000 horsepower—about one-five-hundredth of his estimate of natural lightning. He was creeping, in order that he might learn to walk later. A volt is the standard unit of electromotive force or electrical pressure, and an ampere is the unit of measurement of the flow of an electrical current. According to the Steinmetz calculations, natural lightning might represent as little as 3000 amperes —but would have as much as 100,000,000 volts of pressure or force to initiate it.

The first crude generator, which can almost be said to have been born of the accident at Camp Mohawk, was demonstrated in the winter of 1922. What kind of a sight met the eyes of the group of observers in the lofty laboratory room, with its wide windows and maze of apparatus? There were rows of large glass plates, connected by wires to a power-source and wired to a circuit, or "discharge path," in which was placed the small limb of a tree. The glass plates were the condenser, or "cloud," storing up energy until the point was reached when it could hold no more, and electricity was discharged in a quick flash. That was the bolt, and the observers saw the limb split into fragments. Steinmetz told them: "We get a discharge of 10,000 am-

peres, at 120,000 volts; that is, over 1,000,000 horsepower, lasting for a hundred-thousandth of a second. This gives us the explosive, shattering effect of real lightning."

Steinmetz had coated the glass plates with a metal foil and connected them with an electric circuit. The plates were arranged upon two or three wooden racks, and the connection was made in such a manner that the electricity was accumulated in them, just as it is accumulated in a thundercloud by means of raindrops. In this first generator 200 condensers were used, and they could be connected in several ways to allow the use of various voltages.

The advantage of this generator to the research men was that for the first time they had lightning of an important magnitude under control. It was a poor sort, as such things go, but they knew where it was going to strike, and where to watch for the destructive effects. The engineers arranged the lightning path ahead of time, with a gap at one point, and here was placed whatever object they wanted struck. If it were a fine piece of wire, it would glow white from the sudden heat, then disappear altogether. If it were a small tree limb, it would be split into fragments which sometimes were hurled as much as 30 feet away. The discharge was accompanied by a sound like that of a giant firecracker—and this was "thunder."

Shortly before the death of Steinmetz in 1923, a sec-

ond and larger generator was built. It was capable of delivering 500,000 volts, with power of more than 5,000,000 horsepower, but the Doctor never had the opportunity of using it.

A few months before lightning was first made in Schenectady, the Company's laboratory at Pittsfield, Massachusetts, transmitted 60-cycle electric current at 1,000,000 volts—the work of Guiseppe Faccioli and Frank W. Peek, Jr. This 1,000,000 volts in the laboratory preceded the transmission of 220,000 volts in commercial practice, a mark reached in California in 1922. It did not have the characteristics of natural lightning which Steinmetz sought, and it is mentioned here for sentimental reasons. The achievement took place upon the very spot where high-voltage pioneers, the famous Stanley-Kelly-Chesney trio, had pitted their confidence against the conservatism of the early nineties. The only survivor at this time was Cummings C. Chesney, currently the plant manager. Stanley, inventor of the transformer, and his co-worker Kelly, were dead. Looking forward, Pittsfield was to become famous in its own right as artificial lightning headquarters, and Peek particularly was to contribute largely to that fame, before an automobile accident snatched him from his work.

Vastly exciting at the moment to those who took part in them, these things are already history. Steinmetz had literally set a trap for lightning and turned the errant bolt back upon itself, fighting fire with a

combination of fire, curiosity, and patience. Peek had taken up the challenge in the Berkshires, where nature was prodigal with thunderstorms. And soon lightning study ceased to be one man's stunt and became a fertile field where many labored, always with the same aims of conserving life and property. The engineers moved out into the open, to see what they could see, and record it.

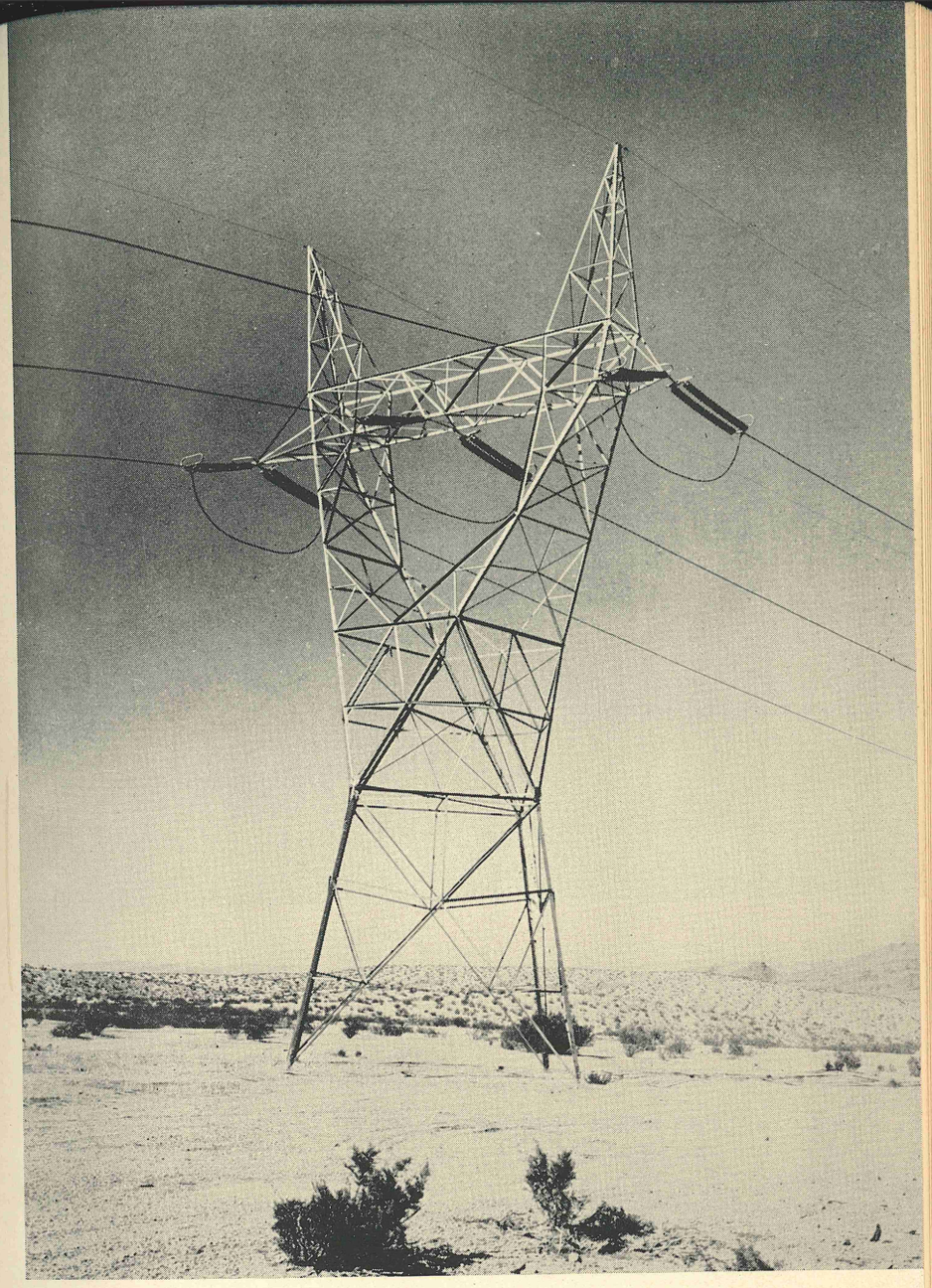
3. FRANKLIN PLAYED WITH FIRE

BUSY establishing the place in current lightning history of Charles Proteus Steinmetz, we have neglected the almost legendary figure of Benjamin Franklin. Diplomat, publicist, entrepreneur, and wit, it is probable that Franklin performed the best-known experiment in electrical history. It is doubtful, in the light of present-day knowledge, if he knew just how much of a personal risk he was taking by flying a kite up into the clouds to discover the nature of lightning. It is an experiment that might not be repeated by many scientists without taking proper precautions—and even then trouble might develop.

Franklin made two important contributions, however, and even though one of them was apparently

founded on a false premise, it has turned out to be valuable. The first contribution, as every schoolboy knows, was that lightning is electricity, and that it has at least some of the characteristics of a discharge from a Leyden jar.

The second contribution, relating to the solution of the lightning problem, was the system of lightning rods which Franklin developed and applied for the protection of buildings. Apparently, he believed that the lightning rod could prevent the discharge from taking place. Having observed the electrical discharge from the pointed rods of the protective system during a thunderstorm, he concluded, because of the visible leakage of electricity from the points, that by thus erecting a series of discharging points he could reduce the voltage between the cloud and the points so that the discharge would not take place until after the threatening cloud had passed over the protected buildings. Today, we know that a lightning rod at the proper height does not prevent the stroke, but we also know that Franklin's system does prevent damage to the structures it is designed to protect, providing that system has been properly installed. In other words, the theory was incorrect, but the practice is correct, a happy mistake which does not dull the luster of the Franklin name. His objectives—what lightning is, and how to guard against its effects—are still recognized as the major objectives in this study.



A strain-tower of the Hoover Dam-Los Angeles 287-kilovolt line of the City of Los Angeles. Note two overhead ground wires at top of structure. Courtesy Bureau of Power and Light, City of Los Angeles.

Edison and Steinmetz examining a porcelain insulator damaged by a laboratory lightning discharge.

Since the day of the famous kite experiment, many investigators have studied the phenomena of the thunderstorm from the meteorological point of view, and today the weather conditions required to form a thunderstorm are quite well known. But, just what is the mechanism that causes sufficient electric potential to build up in a cloud and produce a lightning stroke to the ground, or from one cloud to another, is not so well known.

Parenthetically, the word "ground" is synonymous with earth, when used in connection with lightning strokes. Between the cloud and ground, and between clouds, differences of potential, or voltage, exist because of the thunderstorm process, sufficient to break down the insulating, or "dielectric," strength of the air, with the result that the familiar lightning discharge takes place. The lightning rod system, of which we speak, is one such efficient pathway which we offer to lightning, with the expectation that we may dissuade it from seeking a more destructive channel.

The lightning rod system of protection for exposed buildings has been used since Franklin's day, but its advocates have not always been well informed or too scrupulous in their methods. Often in the past, the expression "lightning rod salesman" invoked either rage or smiles, depending on whether one's experience with that high-pressure gentleman had been at first or second hand. In the years past, lightning rods were applied to

practically every structure on a farm, whether they were needed or not. Today, the basis of application is well understood, and the rods make many buildings safe from lightning damage. We will come back to them later.

In our day, the systems of wires used for the transmission of electricity for light, heat, and power, and for telephone and telegraph service, are a commonplace. As these systems of wires developed, and we came to depend more and more on the services which they supplied, the need for continuity of service became more apparent. When a telephone was a rarity, and every house still had its quota of candles and oil lamps, a break in electrical service was no great hardship. But the penalty of progress is that we continually place more dependence on these modern tools, as we discard those of an earlier day. Today, if lightning damages our system of wires, the lights may go out, the telephone go dead, the radio cease to function, the dinner fail to cook, and the home is reduced to utter helplessness. Then, for the first time, are we aware of the devices we have taken for granted. And thus we set the stage for lightning protection.

When we think of this kind of destruction, we naturally think first of buildings and people, and the measures that can be taken to safeguard them. But for the purposes of our exposition, however, let us for the moment consider another kind of target, the transmission

line, for it is here that the engineer begins to attack the problem. Transmission lines, because of their exposure, their extent, and their location, are probably struck much more often than you realize. When a transmission line (without protection) is struck, it reacts, as we have just noted, in a manner extremely prejudicial to the comfort and convenience of the persons who depend upon it for electric power. Throughout our lightning story one fact will appear again and again. Although lightning itself is usually (but not always) the villain, it frequently sets in motion other forces which are highly destructive, such as fire and explosion.

In erecting a connected system of wires, or "conductors," as we call them, since they conduct electric current from one point to another, whether for the purpose of transmitting electric current to provide for all sorts of services in a home, or for purposes of communication by telephone and telegraph, it is necessary to insulate them from the earth. The earth itself is a conductor of electricity, and the useful current carried by the wires cannot be allowed to "go to ground" and escape. For this reason, then, and also to keep the wires out of the way of human traffic, conductors are strung up on poles or towers. They are also insulated from the structure which supports them by the use of glass or porcelain insulators. The size, and especially the length, of these insulators, is dependent upon the potential, or voltage, of the system in question. In other words, the

higher the voltage, the greater the electrical strength required by the insulators which separate the wire from its supporting pole or tower.

Telephone and telegraph systems operate at relatively low voltage—a few hundred volts at the most—and the insulation required to keep the current from leaking to ground in any appreciable magnitude is of a low order. On the other hand, the great transmission systems which span the country and supply the electricity needed for domestic and industrial purposes operate at a very high voltage and require a considerable length of insulation. They are comparable to great water-supply systems, or aqueducts, which connect towns to the main reservoir or pumping station. For purposes of efficient transportation, whether the commodity be water or electricity, large-volume trunk lines are used, and these are tapped, or "stepped down," later to serve domestic needs, arriving in our kitchens as a small stream from a faucet or the familiar 110-volt household current respectively.

The highest-voltage electrical system in the United States is that which connects Hoover Dam with the City of Los Angeles. The potential between its conductors is 287,000 volts, and the strings of porcelain insulators employed to keep this vast power supply within bounds while it is in transit are 10 feet in length. To insure continuous operation of this line, the conductors are separated at least 24 feet. The hollow cop-

per conductor is 1.4 inches in diameter. The large diameter is for the purpose of preventing appreciable amounts of electricity from escaping into the air as a corona discharge. If the clearance between conductors, and between the conductors and the grounded tower, were not sufficient under storm conditions such as high wind, the conductors might come too close together and the electricity would jump across the gap. The resulting current flow would damage the conductors, as well as the equipment in the station, if the transmission line were not immediately disconnected from the power source. The disconnection is accomplished by the use of a device called a circuit breaker. As the name implies, it automatically breaks the electrical circuit, preventing damage to valuable apparatus, but causing an interruption in electrical service until the cause of the condition is repaired. Insulators, at Hoover Dam and elsewhere, are so designed that when an abnormally high voltage occurs, a flashover will take place through the air or around the insulator. In effect, the insulator does its protective job as long as possible, then figuratively steps aside and lets the torrent pass to ground. If the insulator in the path of an abnormally high voltage did not allow a flashover, it would be punctured and rendered useless for further service until replaced.

This brief reference to the physical characteristics of a transmission line, and to its elemental protective de-

vices, has a direct bearing on the matter in hand, for it is lightning that is the chief cause of these unexpected surges of dangerous magnitude along a line. When lightning strikes, it has a habit of disrupting the orderly channel which the engineer has built to carry his vital electric current. When that channel is disrupted sufficiently, a city's power supply fails, and the engineering problem suddenly assumes human interest, ranging from the merely disturbing to the very serious. A bridge game may be interrupted, or a delicate brain operation in a hospital may fail.

The mechanics of such an accident are interesting, and they bring us back to the earth where we began. The earth is a conductor of electricity, as we have seen, and like a wire or piece of metal or any other conductor, it imposes a certain resistance to the passage of the current. This resistance of the earth varies from place to place, as tests in various localities have shown. If a connection is suddenly made between the earth and the overhead wires which are normally insulated from it, the effects may be very disturbing. Lightning, leaping from wires to ground, causes such a connection to be made, and, in the language of the engineer, this is known as a ground fault.

A single ground fault, that is from one conductor to ground, on many electrical transmission systems will cause the circuit breaker to open and will result in an interruption to normal service. On other systems, faults

to ground on two conductors are necessary to produce this result. Communication systems, with their characteristically low operating voltage, can sometimes continue in service with one of their wire lines continuously grounded, but such operation is not satisfactory.

Between wires and ground, of course, is the air, normally a non-conductor of electricity, but when a sufficiently high voltage is applied to air, it breaks down and becomes conducting. This is what happens when a lightning discharge takes place. Laboratory investigations, which will be described in due course, have supplied valuable information concerning the voltage necessary to cause such a breakdown of the air, for distances up to 30 feet.

It is not difficult to understand, therefore, what happens when lightning strikes a transmission line which consists of conductors supported by insulators attached to steel towers. The steel towers are connected to the earth, and represent a good conducting path in case the insulating value of the insulator is destroyed. When lightning strikes the line conductor, the potential at that point begins to rise swiftly, often becoming great enough to cause the insulator to flashover. The lightning current which got into the line before the insulator did flashover travels along the line in each direction away from the point struck—these traveling waves may do damage at some remote point.

When the insulator does flashover, the power cur-

rent plays "follow the leader" and jumps over the path created by the lightning—and electrical service along that line is interrupted.

Lightning has not changed at all since Franklin's day, nor has the air or the earth, speaking electrically. Man has merely interposed a number of complicated systems calculated to render his existence more pleasant. When the refinements of any mechanism are increased, complications ensue. But the same progress which multiplies our troubles seemingly provides new tools with which we can solve them. Because we dare to harness electricity to turn the wheels of industry we have a longer frontier to defend, and the first step in any defense lies in learning of what the attack consists. Already we have thrown up many barriers as a result of that knowledge.

4. DAMAGE AND DEFENSE

THE importance of continuous electrical service, from the point at which the electricity is generated to the point in the home, or factory, or hospital where it is used, does not need to be established. Since the transmission lines carrying this electricity are among the most attractive of the targets which lightning selects on its way to ground, it was only natural that the same lines should be picked for the opening moves of the defense. The protective devices evolved by the engineers, once they obtained a good grip on the problem, have been generally successful. An understanding of the way in which they perform their protective task is valuable since it sheds light on the habits of lightning.

Some of the most common protective devices can be

found along almost any electric power line supported by poles or towers, and each performs its appointed task in a different way. One corresponds roughly to an umbrella held over the power line to shield it from irresponsible bolts. Another acts somewhat in the manner of a trap or bottle into which lightning is enticed and the aperture tightly corked up. A third acts to neutralize the effect of the fault in much the same manner as the doctor gives an antidote to neutralize the effects of the poison you took to end it all. A fourth method is to disconnect the line so quickly that the fault has no time to burn the conductors at the point of fault, and reconnect the line after the arc has ceased but before an interruption is noticeable at the point where the power is used. This last method is called "automatic reclosing." The fifth functions as a safety valve on a steam boiler, only coming into use when the electrical pressure exceeds the normal and then taking itself out of use when the pressure again returns to normal.

Lightning protection, even in simple forms, is a relatively expensive business, and it is not always justified. Consideration must be taken of storm frequency in a given area, how much valuable apparatus is likely to be damaged by lightning, and how inconvenient, costly, or dangerous an interruption to service is likely to be. In most instances, however, the innocuous-appearing protective devices pay for themselves many times over

in safeguarding the lifeline of electric service 24 hours a day.

In considering how to protect a transmission line—and we demonstrated a few pages back how the "legitimate" energy it carries can be stampeded by a stray lightning stroke into breaking bounds and going on a rampage—the simplest answer would seem to be some method of keeping the lightning away from the conductors. In other words, if some means could be provided of interposing a grounded conductor between the transmission line and the cloud—a sort of lightning rod—then the trouble would be averted. This is the "umbrella" effect, and it is achieved by what is called an overhead ground wire. This wire is made large enough in diameter to carry practically any lightning current without becoming damaged. It is also sturdy enough to withstand the effects of sleet and wind, and can be made of steel if desired.

The overhead ground wire, or wires, since sometimes two are required, is so placed above the conductors to be protected that it will intercept the lightning discharge before the latter reaches the all-important power conductors. To give it a "ground" characteristic, this wire is connected to the earth at frequent intervals. This can be conveniently done in the case of an electric line supported by steel towers by connecting the overhead ground wire to the towers themselves, which are properly grounded at their bases. In the case of the

more familiar wooden poles, down-wires usually placed on each pole are connected to the earth at the bases of the poles. If this were not done at the required intervals, sufficient potential would pile up at the point struck by lightning so that a flashover would take place, resulting in the interruption to service described previously. Furthermore, the lightning might split the pole. The reason for the frequent connections between overhead ground wire and earth is the same as that which dictates that lightning rods be connected to ground as directly as possible. One of the old sayings is that "lightning abhors a corner," but lightning does not dislike a corner as much as it dislikes to travel any considerable distance before it reaches the ground. The shortest path is always best. If the lightning stroke were forced to travel too far along the overhead ground wire before it found a connection to the earth, it would jump to the electric line immediately below and the designed protection would go for naught.

It is not only necessary to have the down-connections from the overhead ground wire made frequently, but the connection to the earth must be good, i.e., of low resistance, otherwise the lightning current in trying to pass into the earth meets enough resistance so that a high voltage appears between the tower and the earth. Since the transmission conductors are insulated from the tower, the same voltage will appear across the insulators and may be high enough to cause the in-

sulator to flashover. The overhead ground wire acts as a horizontal lightning rod and must be well grounded just like the lightning rod on your home.

The overhead ground wire is a shield. The other types of devices to be described go into action when the service line itself has been struck, or its insulation has suffered a flashover, and are designed as cures rather than preventives. The simplest is that which we said resembled a corked-up bottle. Known as a protector tube, this device consists fundamentally of a fiber tube so arranged that the lightning passes through it in preference to subjecting the insulator string to a flashover. An innocent-looking gadget, the protector tube is installed along the electric line in parallel with the insulators, which is an engineer's way of saying that it offers lightning the same opportunities for a quick getaway that the insulator does. In fact, the opportunity is even more attractive, for it will be remembered that when a lightning stroke finds its way to ground (via the pole) blocked by a porcelain or glass insulator attached to the conductor, it takes to the air and circles the obstruction. The protector tube is so constructed that it offers a shorter path, and the lightning takes it. What happens?

As was pointed out previously, when the lightning discharge jumps over the insulator string, the insulating property of the air is destroyed, and the power or system current follows to ground and causes an inter-

ruption to the flow of power through the operation of the circuit breakers. With the protector tube the same power current, or "follow current" as it is called, also follows the lightning discharge through the tube, but it is the follow current which stops its own flow, due to the design of the tube, within a hundredth of a second, which is a time short enough to prevent the circuit breakers from opening the circuit. An interruption to service is prevented, the lightning itself goes to ground, and possible trouble is avoided. Even the least technically minded must admire the swift effectiveness of this small guardian of the transmission line, with its uncanny ability to slam the door in the face of a high-powered adversary at precisely the right split second.

The third device mentioned for protecting service, called the "ground-fault neutralizer," or Peterson Coil, is installed in the power station substation. With this device in action, the current in an arc to ground will be kept to such a low value that the arc quickly extinguishes itself without the users of the power ever knowing that there had been a fault. Someone said this device is like the cowboy in the movies who races his horse beside the runaway horse of the heroine, rescuing her when his speed neutralizes the speed of the runaway horse. In any event, the ground-fault neutralizer robs the arc of most of its strength, and it soon goes out without anyone having been conscious of its existence.

The fourth method, "automatic reclosing," involves the use of circuit breakers, but it has had to await the development of circuit breakers capable of opening the circuit quickly enough. When lightning strikes, a device known as a relay determines which circuit breaker on the system is to open. After about a fourth of a second, the breaker closes, and if the fault has disappeared the line stays connected and service is resumed with hardly a flicker of the lights. Sometimes, however, the fault persists, and the breaker must open again, and stay open, until the fault is cleared.

There has been considerable discussion in previous paragraphs of the mechanics of the lightning stroke as it strikes the transmission line, justified by the importance of that occurrence as it is translated into terms of everyday living. As already noted, when lightning strikes a transmission line and causes the insulator to flashover there is a certain portion of the original wave which travels on over the transmission line into the station, and protection must be provided at that point. Here, we find transformers for changing the voltage and current of the power system as required for efficient transmission, and perhaps generators or motors are also present. These are costly and complicated devices, and must be protected against excess currents which might destroy them. As already indicated, this is the purpose of the circuit breaker, by the use of which the engineer is able to disconnect lines or ap-

paratus in trouble. The use of overhead ground wires, the protector tube, or ground-fault neutralizer, largely eliminates one source of short circuit resulting from lightning. In those cases where a short circuit does occur, it is better to interrupt the electrical service momentarily than to injure or destroy the machines, as this would mean a very long interruption.

Damage may come from a direct stroke to the station itself. This type of damage may be averted or diverted by overhead ground wires suitably placed over the station, or through the use of protective masts. The insulation of apparatus may be damaged by the application of too high a voltage just as the conductors in electrical machines may be overheated by the forcing of too much current through the machines. To protect the apparatus against sudden increases in potential due to lightning, another device known as a lightning arrester has been developed, and it is this that works like a safety valve on a steam boiler. The lightning arrester is a more complicated device than the protector tube, and it must hold the lightning voltage to a lower value. This is necessary if such a complicated structure as a transformer, a generator, or a motor is to be protected.

When the pressure of a steam boiler reaches a determined number of pounds per square inch, the valve, as is well known, opens and allows some steam to escape, thus relieving internal pressure. The alternative is for the boiler to burst. When the pressure returns to a pre-

scribed value, the valve closes. Similarly, the lightning arrester, which is connected between the transmission line and the ground, watches constantly for a sharp rise in electric potential such as lightning causes when it strikes a line and a portion travels to the station. The arrester is a closed valve; it allows no current to flow through it until the potential attains a certain value. At that precise moment, it changes roles. Instead of being an insulator, it becomes a conductor, and ushers the unwelcome surplus energy hastily to ground. When the lightning discharge has passed, a small current may flow for less than a hundredth of a second, but as soon as the potential has again become normal, the arrester reverses itself, the "valve" closes, and current is confined to its regular channel. Thus, for a brief moment of crisis, another inanimate device, having no moving parts and no human direction, throws itself before the complex structures in the power house and shields them from the outlaw lightning surge which would cripple their effectiveness.

Telephone and telegraph engineers have also had to develop protective devices, but they are of a different type, used chiefly in the central office, at cable terminals, and in the homes of subscribers. Because much less electrical energy is involved in this kind of service, telephone companies are not particularly bothered by flashovers due to lightning, except when it damages poles or cross-arms. That, however, is another story.

The protective devices used are much simpler, and their purpose is primarily to protect apparatus and cables from voltages due to lightning.

It has been intimated before in this chapter—and probably no intimation was needed—that more exciting subjects than overhead wires might be found to ornament the story of lightning. If these recent pages have trudged rather than tripped, it is hardly lightning's fault. Nevertheless, those who will take the pains to examine the slow-motion story of cause and effect will better understand the flash; and that is one of our objectives. No economist would apologize for exhibiting a lively interest in transmission line protection, for its significance in dollars is being widely demonstrated. We know now, as a result of field studies, that in some sections of the United States, where lightning is prevalent, there may be as many as 40 flashovers a year for every 100 miles of transmission line. On many power systems, lightning was long the primary cause of disturbance. On some systems it still is, but in general an excellent job of lightning protection is being done.

Overhead conductors are probably struck by lightning more than other man-made projections, because of their number and extent. Each represents an investment; each represents a service upon which many persons depend. Protection of power and communication against the ravages of lightning will continue to be important and instructive in its contributions to progress.

5. HOW MUCH? HOW FAST? HOW LONG?

PROTECTION against lightning damage, as a science, has much in common with such other sciences as flood control and fire prevention. It is a continuous process of locking the barn door after the horse has been stolen. When a great river goes on a rampage, the resulting disaster breeds better dams and shelter belts. Forest rangers' towers, typhoid serum, fire escapes, submarine rescue chambers, and even mosquito netting are all products of man's hind-sight inventiveness, and although the uses of adversity may not be immediately sweet, they leave us wiser and better armed for tomorrow.

Too often, the individual upon whom lightning lays its hand is a complete casualty, and his experience,

whether or not it proved fatal, offers little of value to the investigator. With a machine or an inanimate object the situation is somewhat different. Since it is a better-understood and less complex mechanism than the human body, it remains as valuable evidence of the power, the method, and even of the fallibility of the force which wrought the damage. Many a power plant engineer, observing the destruction caused by an electrical storm and reckoning the cost in time and money, has wistfully wished he might rely on that popular conviction that lightning strikes but once in the same place. Unfortunately the old adage is romantic, not scientific, for there is nothing in nature that will prevent lightning from striking 10, or 100, or 1000 times in the same place, unless it be the complete destruction of the selected object. On the contrary, the fact that a bolt has struck and gone to ground at a given point is eloquent and sufficient warning that lightning can strike in the same place again.

Not only are buildings, towers, wires, and machines more likely to be damaged by lightning, and more valuable to the lightning research engineer after they have been damaged than any human beings, but the considerable amount of damage caused in this category has directly inspired the counter-attack. It has been vitally necessary for electric service companies and manufacturers of equipment which generates, transmits, and utilizes power to discover just what takes place in a thun-

derstorm, and build improved apparatus which will render the lightning charge innocuous. For more than 60 years the business of supplying electric power and communication has been developing. But only for two short decades has the protection engineer made much headway against lightning.

In the beginning, it was necessary to follow the stroke and pick up the pieces, as Steinmetz did at his camp on the Mohawk. The characteristics of lightning had to be determined, or guessed at, on the basis of what it did during its brief, destructive visit. In short, the difficulty was twofold: lightning could not be measured, and it could not be reproduced for study. The guesses were amazingly good, considering the handicap, but there came a time when more exact knowledge was required.

"I often say," declared Lord Kelvin in a famous lecture before the British Institute of Civil Engineers more than a half-century ago, "that when you can measure what you are speaking about, and express it in numbers, you know something about it; but when you cannot measure it, when you cannot express it in numbers, your knowledge is of a meager and unsatisfactory kind; it may be the beginning of knowledge, but you have scarcely, in your thoughts, advanced to the stage of Science, whatever the matter may be."

More than one man, with tired arms and back, has gone into a shop to buy a motor without the slightest

knowledge of the horsepower, speed, or voltage required, or even being informed as to whether his power supply was of the direct- or alternating-current type. The shop owner may well reply that he must know all of these things before he can supply the required motor.

This was approximately the situation facing power companies and electrical manufacturers concerning the required characteristics of lightning protection equipment. The power companies had to have machines that would continue to render service during electrical storms. To fill the order, the manufacturer had to have proper measuring instruments, and lightning to measure. The measuring instruments had to come first. Once the characteristics of lightning were known, it was thought that it would be possible to reproduce them in the laboratory, make them perform at the will of the ringmaster, jump through hoops, strike miniature lines, split tree trunks. The engineers were especially curious to know how a complicated structure like a transformer, which consists of two or more windings insulated from, and encircling, an iron core, would react to the impact of a lightning discharge.

It would seem that the normal procedure for such a study as the manufacturers and utilities undertook cooperatively would be first to find out all they could regarding natural lightning, as it occurred along the power lines, then duplicate their findings in the labora-

tory. Actually, the process was reversed. Instruments had to be devised before taking to the open country. Also, laboratory tests can be made at will, once the equipment has been organized, while natural lightning must be waited upon. It has its seasons and its peculiarities. As slow as lightning is fast, is the steady accumulation of statistical data with reference to discharges, because no two are exactly alike.

Undeniably, patience has been the most frequently used tool in the kit of the lightning hunter. To the imaginative, nothing has seemed less predictable or more scornful of the earth and its creatures than has lightning, striking and receding and striking again in a moment so brief that it has to be measured in millionths of a second. So there is a certain grim and thoroughly human satisfaction in observing this fleet elemental scourge being slowly and steadily rendered harmless in the coils of human understanding. To gauge that achievement properly, we must turn back to the Steinmetz laboratory in Schenectady, follow the trail to a more modern establishment in the Berkshires, and finally train our sights on the very tip of New York City's world, the mooring mast of the Empire State Building.

6. MEN MAKE LIGHTNING

MAN-MADE lightning has a hypnotic quality about it that tends to suspend the thought processes of observers. It is the modern counterpart of alchemy and witches' brew, except, perhaps, to the engineers who are engaged in reducing its measurable effects to cold figures, and it exercises a spell upon observers that is somewhat akin to the licking tongues of flame in an open fire or the swaying head of a circus cobra. Fire and flame have always played leading roles in savage rites and pseudo-supernatural manifestations. Every fakir in every age has been aware of this quality, and has used it to play upon the senses of human beings. When we have had occasion to employ our modern lightning-making machines purely for the amusement

of visitors to the laboratory, the latter's reactions and facial expressions are fascinating to watch. Audience emotions range from a nervous and self-imposed calmness to hysteria and downright elemental fear as the high-potential arc splits the darkness and the bolt crashes through space, echoed by the steel walls of the laboratory room.

If it is our duty to point out the matter-of-fact, logical reasons for manufacturing lightning and measuring its effects, it can also be our pleasure to describe, for those who have never seen it, the spectacle itself, and the machinery which creates it in nature's image.

To begin somewhere near the beginning, although static machines, Leyden jars, and charged lead-sheathed cables had been used for some time to simulate lightning discharges in the school-room and the laboratory, the first serious attempt to duplicate the real effect began with the construction of the 120,000-volt lightning or impulse generator in 1921 in Schenectady by Steinmetz. This was followed two years later by the 500,000-volt generator. The first generator, which consisted, as noted previously, of condensers made of glass plates with metal foil on either side, was charged through the use of the newly developed kenotron tube, which could change high-voltage alternating current to direct current. This generator was capable of splitting blocks of wood when the discharge was directed through them.

A lightning discharge, whether natural or artificial, consists of a rapid discharge of electricity. The current in the stroke mounts swiftly to a peak, then subsides more gradually, and it is the practice of engineers to express this rise and fall graphically by means of a wave. The height of the wave is a measurement of the voltage or current being discharged; the horizontal measurement, of course, represents time. Since these waves will make a frequent appearance in this story, it would be well for the reader to seize upon this brief explanation of the term. Most lightning waves have an exceedingly steep front—in other words, the current builds up very rapidly in point of time—and the actual contact of the lightning stroke to the earth or to ground is believed to occur at the peak of the current, after which the current drops off gradually. Some strokes have a succession of peaks, or pulses, of current. The means by which engineers cause lightning to thus write its autograph when it strikes will be disclosed a little later.

At the time the Steinmetz generator was causing smiles and raised eyebrows around the Schenectady plant, however, no one knew whether the wave-form produced by discharges from the apparatus was similar to that of natural lightning or not. It was only known that (outdoors) electrical charges were in the cloud overhead, and charges of the opposite sign were in the ground underneath. It was not even known which was positive and which was negative. The earth-charges

were separated from the cloud-charges by air, and the air was a non-conductor of electricity.

The laboratory lightning machine simulated nature in certain respects. It caused a condenser discharge to take place between two conducting points, or electrodes, when the electric potential was great enough to break down the air between them. Although with this impulse generator, and some of the larger ones built subsequently, it was possible for the engineers to split wood and produce a weak imitation of outdoor thunder, we know today that there are vast differences between such a generator and nature's original machinery. One such difference is that a cloud is not a conductor, as is the foil on the glass plates of the condenser, but instead a collection of drops of water or particles of ice separated from each other by insulating air. Also, within a single cloud or cloud-mass, both positive and negative charges exist. The lightning stroke itself is not a few feet long—our poor imitation—but hundreds, or frequently thousands of feet in length. Finally, we know that the earth is not a perfect conductor on its surface. In spite of these differences—and only within the last few years have they been recognized as important—much valuable data on the performance of insulation and apparatus were obtained by the early generators. Because they did not know what the wave-shapes of lightning might be, the laboratory men endeavored to investigate enough different conditions so that nat-

ural lightning was certain to fall somewhere within their range. They were using buckshot to bring their prey down, a good idea, but one that has its limitations as any hunter will testify.

As time passed, the need for knowing more about this handwriting of lightning, expressed in waves, became more apparent. Following Steinmetz, F. W. Peek, Jr. increased the voltage and capacity of the impulse generator in General Electric's High-Voltage Laboratory at Pittsfield until, in 1928, the then "big gun" had a potential of 3,600,000 volts, obtained with an initial energy of 8100 watt-seconds. Reduced to household terms, for easier understanding, this meant that Peek was using the electric current represented by 81 100-watt lamps, burning for one second. With it, aided by his apparatus, he was producing a discharge having the pressure (voltage) equal to 30,000 times that found in the ordinary 120-volt household electrical circuit. As Goliath discovered to his dismay, when struck down by David, it is not so much the size of the missile which counts as the force which propels it.

Lightning research, once begun, was a rapidly moving study, however, and Peek's giant slingshot was shortly to be regarded as "pioneer" apparatus, despite the valuable work which was achieved with it. It had certain drawbacks which limited severely its further development. The old Steinmetz method of charging the laboratory "clouds" or condensers by means of the

kenotron tubes had been discarded, and high-voltage transformers were used for this job according to a unique method developed by Peek. Transformers are expensive, and, as time passed, it became apparent that laboratory lightning produced by such a method in excess of 3,600,000 volts would be very expensive and require considerable equipment and floor-space. Another drawback was that the polarity (negative or positive) of the impulse generated was difficult to control.

The solution of these difficulties came with the description by E. Marx, in 1925, of a new type of impulse-generator circuit. The method need not be described here except to say that it was a simple method of charging the condensers, or capacitors as they are now called, in parallel and discharging them in series, and that it removed the limitations on maximum potential which had previously existed. It is especially interesting to note that the development of the Marx circuit in effect put man-made lightning in a suitcase and freed it from the laboratory enclosure. Within a year or two, a 1,000,000-volt portable lightning generator was built and transported several hundred miles from Pittsfield. On location, it was used to produce modest lightning bolts and hurl them at the transmission lines of utility companies, so that field engineers could study the results right on the firing line, diagnose the trouble, and recommend a cure. To be able thus to snatch lightning bolts from their pockets and make them perform at the

end of a leash, despite the persistence of a cloudless sky overhead, was no mean achievement.

After the development of the Marx circuit, artificial lightning generators of increasing capacities were built both in the United States and abroad. The climax, at least at the time of this writing, came with the building in Pittsfield of an impulse-generator able to produce 10,000,000 volts of artificial lightning. This result was obtained with an initial energy of 124,400 watt-seconds (reverting to simple arithmetic again, the energy represented by 1244 100-watt incandescent lamps, burning for one second). A similar generator, with an output increased nearly 50 per cent, was built for display at the New York World's Fair in 1939. Because it is the streamlined, modern-mannered child of a long line of humble but worthy parents, and because its crashing voice and spitting fire have succeeded in entertaining or frightening literally millions of visitors, let us focus on it for the promised description of man-made lightning at its most impressive stage.

Lightning generators, as has been made evident in the foregoing pages, have a definite place in the research scheme. They are not toys or side-show attractions, but delicately adjusted, complex mechanisms. Nevertheless, with as many as twenty "shows" to play each day for the crowds on the Flushing meadows, the World's Fair generator functioned faithfully and without serious interruption during the exposition months.

Variously dubbed a "pawnbroker's nightmare" and a "high-potential tinkertoy" because of its collection of knobs and stacks in black and chromium, the generator was the leading actor on a stage that might have been provided by H. G. Wells as a background for a book on Mars. In actual size it was smaller than its workaday predecessor at Pittsfield, occupying less than a quarter of the floor-space taken up by the latter. New style capacitors, replacing the older condensers, serve the same function as clouds in a natural thunderstorm, and were designed to make possible the building up of high voltages pending their swift release as artificial lightning. The capacitors, insulated with a non-inflammable fluid known as pyranol, were cylindrical, or drum-shaped, and were mounted on each other to form stacks 34 feet high.

The 10,000,000-volt generator really consisted of two separate and complete generators rated at 5,000,000 volts each. Each unit was made up of six vertical stacks of capacitors, insulated from each other by herkolite cylinders, painted black. The two units faced each other in a long, high-ceilinged chamber, along one side of which was extended a balcony for the convenience of visitors. In a cleared space between the two units were placed the various objects to be struck during a demonstration. Along a wall facing the spectators were transformers and other apparatus, and a high enclosed cage from which the engineers directed the demonstra-

tions. The appearance of the room, with the house-lights lowered and red signal-lamps glowing, with the tall, forbidding stacks of black and chromium from which protruded shiny sphere-capped rods in weird profusion, was enough in itself to quicken the lay-watcher's pulse, and his feeling of tension and uneasiness was usually somewhat heightened by the sharp odor of ozone which pervaded the atmosphere as a result of past demonstrations.

The banks of capacitors, or stacks, take the place of the banks of cumulus clouds in nature. They are the thunderheads of the lightning generator, and are rapidly charged until the desired voltage is reached. Then they are suddenly discharged, just as nature's cumulus clouds are discharged by a lightning bolt, and the discharge makes a bright arc 30 feet in length from the foremost point of one generator to a similar point on the other, accompanied by a loud crash. The path of the discharge is seldom, if ever, straight, and frequently branches may be seen, as in the case of natural lightning. If one looks directly at the air gap between the electrodes, or terminals, when the discharge takes place, the light of the flash leaves an impression on the retina of the eye for some moments after it has occurred. While this image persists, the path of the discharge may be seen again whenever the eyelids are closed. So accurate is this image that engineers studying lightning

flashes in the darkness often depend upon it for their review of the arc.

The stored energy of the 10,000,000-volt machine is 165,000 watt-seconds. If that energy were released slowly, as through a single incandescent lamp, it would operate a 100-watt lamp for almost a half-hour, but in the lightning discharge this energy is released in a very few millionths of a second. The power, or the rate at which it is released, is therefore very great. As operated, the total amperes produced are 17,000, and that is about 20,000 times the current required to operate the same 100-watt lamp we have just mentioned. For a discharge of 10 microseconds, or ten-millionths of a second, to carry these mathematics a little further, the rated power output is 16,500,000 kilowatts, more than 13 times the total electric power developed at Niagara Falls, or more than 45 per cent of the rated generator capacity of all the electric power stations of the United States. A solid copper conductor, to carry 17,000 amperes continuously, would have to be five or more inches in diameter. Actually, a small wire (0.04 inch in diameter) can carry this huge current from the lightning generator, because of the short duration of its flow.

Fifteen seconds is required for the lightning generator to reach its full value of charge before discharging across the 30-foot gap, and during this interval the hum

of the apparatus imparts an ominous note which is quite in keeping with the weird spectacle.

One of the demonstrations commonly performed for spectators with the lightning generator is the splitting of a hard maple post. When the discharge is made to pass through the wood rather than over the surface, the post is violently blown apart. When the split pieces are examined it is found that there is a fine line in the wood indicating the path of the discharge. The wood along this path has been turned into gas. The sudden vaporization produces a high gas pressure which is not relieved until the wood splits, the action being similar to that of a dynamite explosion. For a short time after the demonstration, the wood pieces give off the odor of the gas, which is much like that given off during the fractional distillation of wood. Log-splitting offers one of the best instances of the damage that may be wrought by lightning.

In another demonstration the artificial lightning is discharged to ground through a length of fine wire. In the small fraction of a second during which the discharge lasts, the wire is first melted, and then vaporized, so that it is completely destroyed amid a shower of sparks and vanishes altogether. Various other "stunts" include striking models of wooden buildings, blowing out their windows, and under some conditions setting them on fire, to indicate once more the "trigger"

action of a lightning bolt which tends to release damaging forces of a more mechanical nature.

Not falling strictly in the artificial-lightning category, although definitely a high-voltage phenomenon, is another demonstration frequently given in the laboratory because of its beautiful effect, lasting over a period of minutes. It is the 1,000,000-volt, 3-phase, 60-cycle arc, and is worthy of description because it presents a sort of slow-motion picture of high-voltage action. In this demonstration, electricity generated at 2300 volts is stepped up by three transformers to a point where the voltage is nearly ten thousand times that used for ordinary house lighting. The arc produced is spectacular, but makes little noise. The high-voltage is applied to a three-phase spark gap consisting of three electrodes arranged in the form of an equilateral triangle and spaced approximately nine and one-half feet apart. Each electrode consists of a horizontally mounted pinwheel.

These pinwheels rotate freely, without being mechanically driven, as a result of the phenomenon of discharging points, which causes them to be pushed backward in the same manner in which a rocket is propelled by its burning powder. The pinwheels come up to speed as the voltage is increased to 1,000,000 volts.

For this demonstration also the laboratory is darkened, and, as soon as the voltage is applied, a beautiful violet glow appears on the pinwheels and on the wires

connecting them with the power supply elsewhere in the room. As the voltage is increased, this glow becomes more and more marked, and a loud hissing noise is produced. The voltage is so great that it endeavors to escape from each rough spot on the connecting wires, like high-pressure steam escaping from a leaky pipe. In order to prevent this visible loss, a smooth conductor six inches in diameter would have to be used.

When a potential of 1,000,000 volts has been attained, a flashover takes place between the points, and this fiery, lacy arc is maintained although air currents carry it as much as twenty feet above the points. The normal color of this arc is steely blue, but with an unprofessional (and certainly unscientific) flair for the spectacular, the laboratory men usually have placed chemical mixtures on the electrodes in advance, and these are ignited. The metallic vapors of the substances used (strontium nitrate for red, sodium chloride for yellow, thallium nitrate mixture for green) not only paint a fascinating colored picture, but greatly increase the conductance of the arc, thereby justifying its use without recourse to the aesthetic. A greater current flows, and the entire room is illuminated. The lacelike effect, caused by the use of alternating current, may readily be seen. The arc, in effect, "goes out" 120 times a second as the current passes through zero, and the dark bands provide the lacelike effect. The progression of the color through the arc may be easily traced

through the use of motion pictures taken in natural color. Often two colors or even three can be observed in different parts of a single arc at the same time.

The discharge attempts to continue through the path of the least resistance, which now is through its own broken-down and heated air path; but this warm air, in rising, continually lengthens the path, and it eventually becomes so long that it can no longer maintain itself. The arc then goes out, and a new arc immediately forms in a new path lower down, only to start rising again. This effect will continue as long as the voltage is maintained by the operator. Each arc pattern is different in form, mobility, and color—one of the most entrancingly beautiful sights to be seen in a laboratory.

Sixty-cycle alternating current, with a potential of 1,000,000 volts, will jump 9 feet. A 60-cycle voltage of 10,000,000 volts would jump about 90 feet. The distance which a given voltage will jump across most types of gaps depends, to a large extent, upon the length of time that it is applied. With lightning, voltage waves rise so rapidly to their maximum value, and drop down to zero or near zero so quickly, that they will not jump nearly as far as if the voltage were maintained for longer periods of time, as in the relatively slow-rising 60-cycle voltage wave employed in the last demonstration described above. A lightning voltage of 10,000,000 volts, lasting but a few microseconds, will jump only

30 feet. This indicates that the rise and fall of voltage in the lightning wave is extremely rapid, and that a certain amount of time is required to produce a flashover. If the decrease of voltage, after reaching a 10,000,000-volt crest, were slow enough so that 5,000,000 volts were reached in 40 microseconds, then the 10,000,000 volt lightning could be made to jump 55 to 60 feet. Which fact, introduced at the end of a chapter devoted to pyrotechnics and entertainment, should impart a sufficiently sober note to indicate that lightning generators are not simply expensive Roman candles. After the last visitor has gone, everyone goes back to work.

7. HOW QUICK IS A FLASH?

WHAT happened when that much-hunted gangster rounded a corner in Chicago and found himself face to face with two G-men? *As quick as a flash* his hand darted to the holster under his armpit, but the sleuths were faster—thanks to a combination of virtue and agility—and with their guns spitting fire, they cut the desperado down. If they had not been armed, it is presumed that they might have turned on their heels and disappeared, like a *streak of greased lightning*. Thus the characteristics of lightning invade the language whether we like it or not.

"Quick as a flash," we repeat at intervals in our daily lives, in careless human fashion, but *how fast* is a flash? More to the point, how fast is a flash of lightning?

Through the use of certain types of special cameras, which will make their appearance later in this story, the investigators have been able to discover that lightning frequently consists of many successive discharges along the same path. The total time used up by these successive flashes, appearing to most of us as a single stroke, may be as long as a second and a half. The time required for a single discharge, on the other hand, varies widely, but an average of 100 microseconds is perhaps not far off.

Microseconds, like billion-dollar debts, are difficult for the mind to grasp and evaluate. A millionth of a second is so brief, so small, that it easily slips through the rather clumsy fingers which nature bestowed upon us for purposes of computing simple sums, unless we can place it under a magnifying glass and dramatize its brevity. A whole second is none too long if we are sprinting to catch a train, but let us divide it into a million parts nevertheless. In one-millionth of a second, an object moving at the incredible speed of a thousand miles an hour does not move one-sixteenth of an inch—in other words, it is practically standing still.

The foregoing may help to illustrate the difficulties which beset us in devising instruments with which to measure lightning, to obtain those cold, accurate figures without which, as Lord Kelvin pointed out, we know little or nothing. The first part of the task we had set ourselves was well on its way to achievement, for we

had produced artificial lightning and had begun to bottle it up, so to speak, for leisurely study. Now we were confronted with the second objective—finding an accurate measuring stick or gauge. Obviously, the ordinary devices for evaluating electricity, in terms of volts and amperes, would not suffice, for they involved mechanical motion, and, as such, were subject to so much inertia in operation that millionth-of-a-second lightning flashes could sneer at them with impunity.

Nature usually provides simple, obvious answers to the problems which she raises, but we are inclined to fumble a bit before we see them. Witch hazel, growing side by side with poison ivy, is an antidote to the latter's infection. Forest fires are best halted by fire. One disease may be cured by inoculation with another, and a thief may outstrip a policeman in catching another thief. To capture the volatile capriciousness that was lightning, we had to employ a medium having similar characteristics.

The engineers who worked with the laboratory impulse-generator developed by Steinmetz realized full well the necessity of being able to measure not only the voltage of the discharge but the time duration. In fact, the whole progress of the study of lightning and its effects in the field and in the laboratory could not be carried forward with much success until a device capable of recording the wave-form of this swift phenomenon was available. The answer was an oscillo-

graph, a device whose nature is indicated clearly by its name, since it records *graphically* the dancing *oscillations* of an electric current.

Imagine that you are standing on a subway platform, your right arm extended straight out in front of you. Further assume that, on account of springs or rubber bands attached to your hand, force must be exerted to move your hand either up or down. For example, a force of one pound might be required for each inch that your hand was moved either up or down from the horizontal or zero position.

In your hand is a piece of chalk, and, as an express train speeds past, you place the chalk tip in contact with the smooth steel side of a passing car. As long as you exert no vertical force, either up or down, the chalk will trace a straight line on the train's side, which line represents the line of zero vertical force. If, however, you move your hand up or down as the train moves past, the chalk will trace a continuous wavy line. One, examining the chalk mark later, would find that it was a graphic record of your action. Assuming a proper calibration, the observer could tell just the force applied in pounds to produce the deflections above and below the zero line recorded. In addition, if he knew the speed of the train as it passed you, he could tell, from the number of waves and the steepness of the "front" and "tail," just how fast you were acting.

In a crude sense this is oscillographic recording, and

the chalk mark is an oscillogram. In the actual device, the role of the speeding train is played by a photographic film which moves at a constant speed. The chalk record finds its parallel in the film's record, and in place of the chalk we use light, which can be made to record the reflections of a moving mirror suitably mounted.

When our lightning research began, such instruments, known as electromagnetic oscillographs, were in existence. They consisted of a loop of fine wire located between the pole faces of a powerful magnet. Cemented to the wire was a mirror. When a current proportional to that to be measured pulsed through the fine wire loop, and when a suitable optical system was employed, this oscillograph would record upon a moving film the same sort of wave-shapes described above, waves which would indicate to the observer how many amperes were involved in the current being measured, and how rapidly the rise and fall was occurring. When the current moved through the fine wire loop, magnetic forces moved the mirror to and fro in a manner which reflected the changes in the current. Such instruments were useful for certain jobs, but for us they had certain rather obvious drawbacks. One was that a certain amount of current was required to operate the oscillograph. Another arose from the fact that the natural period of vibration was about 5000 cycles per second. In this range of frequency, natural frequency

errors are introduced and accurate measurements cannot be made. In the case of lightning the rate of change is often so high and the time duration so short that the deflection system of this type of oscillograph would not move fast enough to make satisfactory records.

The mirror system, being fundamentally mechanical, had inertia. The photographic film could not be driven, mechanically, fast enough to record the very short intervals of time required. Lightning, we thought, was too fast to be caught in this kind of a trap. However, we shall see later that this type of oscillograph did have a place in the recording of lightning.

The need for great recording speed meant that a new measuring device had to be developed, one that would fulfill four specific conditions: (1) it should have no appreciable inertia, comparable to lightning itself, and be capable of operating at a frequency of at least 1,000,000 cycles per second; (2) the device should use so little electric energy in its operation that it would not disturb the original circuit and confuse the results obtained; (3) it should be so arranged that a single impulse would be enough to leave a satisfactory photographic impression, since natural lightning will not repeat itself for our convenience; and (4) the oscillograph should be as simple as possible, and so accurate that its results could be used without question.

It was a large order, but the clue to the solution came from the first requirement we had set down.

What usable force was fast enough and at the same time free from inertia? Obviously, the device had to make use of the flow of electrons, and eventually we turned to the Braun tube, which had been used for many years as an oscillographic device and which was familiar to most frequenters of a college physics laboratory.

For the benefit of those whose training is more literary than scientific, an explanation of the Braun tube is in order. Named after K. F. Braun, its inventor, it is a glass structure from which air has been exhausted to provide a vacuum. Within the glass enclosure are two terminals or electrodes, which have external connections to a source of electric current. The electrode connected to the positive pole of the source is known as an anode, while the negative one is called a cathode. With the cathode connected to the negative pole of a machine producing static electricity (high-voltage direct current) and having a potential of from 60,000 to 80,000 volts, and the anode connected to the positive pole, a stream of electrons passes between the cathode and the anode. The latter, being provided with a central hole, allows some of these electrons to pass through it and spatter up against the glass end of the tube. But electrons, despite their very tangible name, are invisible in their natural state, and an artifice must be employed to make them leave a visible trace. This artifice, in the Braun tube, is in the form of a fluorescent coating on

the inside of the glass, transforming it into a veritable movie screen. When the electron stream strikes the end of the tube, it causes a spot of light and thus the point where the electrons strike the fluorescent screen becomes visible. Now, if the electron stream can be made to move across the screen at a known rate, a time scale would be produced, as when holding the chalk steadily against the side of the moving car. If, at the same time, there could be imparted to the electron stream a motion (at right angles to the time motion) proportional to the change in the electric current being studied, an oscillographic record suitable for lightning study would be obtained.

The impression made on the observer corresponds roughly to what he would see were he stationed on one side of a large plate-glass window, while someone on the other side played a fine stream of water rapidly from left to right, and at the same time up and down across the glass. But we are concerned with a stream of electrons, not a stream of water, and electrons, being infinitely small particles of electricity, are subject to deflection by magnetic and electric fields. Thus, if the electron stream within the tube is made to pass through a varying magnetic field at right angles to the motion of the stream of electrons, the stream would be deflected as the magnetic field varied, and the moving spot would trace what to the eye would appear as a straight line on the fluorescent screen. We do not usu-

ally use magnetic fields, for technical reasons; an electrostatic field is more convenient. Thus the electron stream is made to pass between two sets of plates, each set of two being at right angles to the other set. The electron stream, passing through the hole in the anode, passes between the first set of plates where the electric field is made to vary at a known rate, producing a horizontal deflection of the electron stream, which is the time scale. This moving stream then passes through the next set of deflection plates, between which the electric field varies as the unknown voltage or current to be measured varies. This gives rise to the vertical motion which, combined with the horizontal time deflection, imparts a wave motion to the electron stream so that when it impinges on the fluorescent screen a record of the unknown transient is obtained. And here, at last, we arrive at the explanation of why the Braun tube lent itself so aptly to the measurement of lightning. Incidentally, such a tube is also employed to produce television pictures.

The regular stream of electrons, beating swiftly against the end of the glass tube, and leaving there a clear trace of its movement, is the measuring device. If we assume, without going into detail, that voltage proportional to a lightning discharge be applied to the deflecting plates located on each side of the stream, it is not difficult to foresee how the electrostatic field produced between the plates will distort the flow of elec-

trons, pulling it first in one direction and then in another, and, in so doing, registering that distortion on the "movie screen" at the tube's end. Such a series of distorted waves could obviously be calibrated in terms of voltage and current, or of time and either voltage or current, producing the same kind of telltale picture which we imagined to have been produced on the side of the speeding train with a piece of chalk.

The final solution was not this easy, however. Even supposing that we could force lightning thus to blaze its measured trail in light across a fluorescent screen, we still needed a permanent record of that trail, a record that would stand still while we read its message. Photographing the moving beam was the obvious answer. However, this could not be done, owing to the low intensity of light in the image when the fluorescent screen was illuminated but once, and too briefly.

Scientific progress, as we have noted previously, is the composite march of many feet, and the way out of our dilemma was shown us by a Frenchman, Alexander Dufour, whose duly recorded achievements were all the time reposing on our library shelves. In 1914 he had described a modification of the Braun tube in which he had placed the photographic film within the vacuum chamber itself, permitting the electrons to strike the photographic film directly instead of the fluorescent screen, thus leaving a permanent record. By this means he obtained a registration on the film such

that one twenty-fifth of an inch corresponded to a time of one three-millionth of a second. Later, in 1922, Dufour used in his study of antenna currents in the wireless system of the Eiffel Tower in Paris a modified tube with which he photographed transient currents up to a fundamental frequency of 750,000 cycles, and with some success even at a frequency of 3,000,000 cycles. These were the astronomical figures we sought for our own job, and in 1924 two Dufour oscillographs were acquired.

Even these, while keyed to our problem in one sense, were not adequate in another, for Dufour was working with currents whose timing was not important, and hence easily photographed, while we were playing with lightning—which seems never to strike twice in the same place when you want it to do so. However, we kept at the task of modifying our methods under Dufour's lead, and in August, 1924, one of our men, E. J. Wade of the Pittsfield laboratory, obtained, while using a laboratory lightning impulse, the first oscillogram to be made of the performance of a lightning arrester. Our elusive quarry had finally been persuaded to sit for its first portrait, or rather, had submitted to its first fingerprinting, for later we were to take portraits in earnest. Many improvements were to follow in both the oscillograph and the photographic equipment, until finally it would be possible (as it is today) to photograph, from an external point, the arrivals and

departures of a lightning bolt as recorded by the fleet electron beam. Not only did we have in the laboratory the means for accurately measuring the power and the force of a bolt of lightning, but we had a gun from which we might fire bolts of our own making whenever we chose to pull the trigger. At last we were prepared to go after our big game in earnest.

The likeness to a hunting expedition was apt in more ways than one. It will be remembered that those who suffered most from the depredations of lightning were the power companies, because their ability to furnish you and your family with dependable electric service was threatened by this outlaw who struck swiftly and left behind damaged apparatus and dead wires, to say nothing of disgruntled human beings. With the cathode-ray oscillograph in portable form, and with a portable lightning generator, we were finally equipped to go out into the countryside, create our own lightning storms along typical electric transmission systems, and measure the results.

Not much concentration is required of the average person who watches lightning strike, unless he is concentrating on *not* seeing the bolt. But it must be evident that years of laborious effort were required of the handful of men, here and abroad, who had for their objective the pinning of that flash of fire to a piece of paper or film. Today we can pick up a pencil and in a few seconds draw the wave-shape of a typical lightning

bolt with almost ridiculous ease. But that simple piece of draftsmanship cost a vast amount of time and money; and the fact that we *can* draw it today is saving even more.

Not all the pictures men attempted to draw of a vagrant electric discharge were as simple as the wave, and one in particular was very fascinating. It is known as the Lichtenberg figure, and bears the name of a German scientist who discovered it in 1777, not very long after Franklin flew his kite. Lichtenberg sprinkled powder on an insulating plate, the reverse side of which was connected to one pole of a Leyden jar. The other pole of the jar was separated by a gap from the powdered side of the plate, and the jar was then discharged across the gap. In a modest way, Lichtenberg was going through the motions of hurling a very small fragment of lightning against a surface sprinkled with powder. What happened was that the powder arranged itself in a pattern, much more complex and interesting in appearance to the layman than the modern oscillographic wave. The figure resembles a one-eyed monster, having a circular center, or nucleus, from which a large number of hairlike lines radiate.

One hundred and eleven years later, two other scientists, Brown and Trowvelot, substituted a photographic film for Lichtenberg's insulating plate, and placed the emulsion side of the film in contact with the discharging electrode, thereby securing a permanent record in-

stead of one which would vanish when the laboratory door was slammed suddenly. The queer-looking figures maintained their family resemblance.

It has been pointed out previously that when lightning strikes a transmission line, voltage can rise to certain values before the air around the insulation has more potential applied than it can stand, and then a flashover through the air takes place and the lightning path between earth and cloud is then completed. Knowing something of the electrical strength of the insulator, based on laboratory tests, it was only natural for investigators to look for some means of measuring the voltage of the flashover due to natural lightning.

In 1924, J. F. Peters of the Westinghouse Company decided to use the Lichtenberg figures in a device he called the Klydonograph in an attempt to measure the voltage of lightning. In this device several electrodes, instead of the single original one from the Leyden jar, were used so that several figures could be obtained on a single film. It is obvious that the Klydonograph could not be used to measure lightning directly—that is, it could not be connected directly to the wire which lightning might strike—because the instrument offered no continuous path to ground, and the transient current would leap around it just as in the case of the insulator. Furthermore, the insulation of the device was not such that it could be directly connected to a line in which regular system current was flowing. Therefore, Peters avoided a direct connection to the line and provided a system of his own, one which need not be described in detail here, but allowed him to measure a specified part of the voltage across the line, which, when multiplied by the proper ratio, gave the value of the voltage on the line.

Lichtenberg figures, obtained through the use of the Klydonograph and a later instrument known as a surge-voltage recorder, which could record both polarities of the same stroke, played an important role in lightning research. The diameter of the figures increased as the voltage applied to the instrument increased; also the appearance of the figures created by a positive discharge differed from that caused by a negative discharge. It was found that the diameter of the positive figures increased more rapidly with a given increase in voltage than did the diameter of the negative figures. This made it possible to determine with the Klydonograph whether a lightning stroke on a transmission line was positive or negative, one of the important points that was in doubt when the investigation began.

In 1926 the cathode-ray oscillograph was used to study the effect of different wave-shapes on the appearance and size of Lichtenberg figures, so as to add to our knowledge of lightning as indicated by figures obtained during lightning storms.

One of the first things that the measuring instruments established was that most lightning strokes, as

they came from the clouds, were of negative polarity, and therefore the accompanying surge of electricity induced in the earth directly underneath, as will be shown later, was positive in character. From 1924 to 1930 many installations of Klydonographs and surge-voltage recorders were in service on transmission lines and communication circuits.

The camp of the lightning hunters was pitched on a wide front, and as the quarry was bagged again and again, it became possible to tell from the records that the voltage of lightning strokes, as they appeared on the lines, varied. It was shown what percentage of the strokes were of one voltage and what percentage were of another, and how the voltage of the stroke decreased as it sped along the wire seeking ground.

Thus, the puzzle that was lightning was slowly but steadily being pieced together, by men widely separated not only geographically but chronologically, by scientists in South Africa and research men in Sweden, by engineers in Pennsylvania and in the Berkshires of Massachusetts and by other engineers in the Eiffel Tower in Paris, by a colonial gentleman with a kite and by a German gentleman with a Leyden jar and a pinch of powder, who managed to indicate through the haze of 150 years just how a transmission line might be constructed to function efficiently.

8. GHOSTLY ARITHMETIC

IF ONE would understand the elements of the lightning stroke, the better to satisfy his curiosity and protect himself and his property, some knowledge of traveling waves, their shapes, and their ghostly reflections is necessary.

Armed with our portable lightning machine and our high-speed cathode-ray oscillograph, we took to the field, and in 1929 we were able to make our first report. This covered observations of the effects of sending waves from the 400,000-volt lightning generator over five miles of Massachusetts transmission line insulated for 110,000 volts. This study was undertaken to demonstrate to ourselves and to others how traveling waves performed; and traveling waves are impor-

tant because it is through the medium of the traveling wave that lightning effects are carried from the point struck to other points on the conductor.

Later we moved our portable lightning apparatus to Michigan, and for three successive summers our engineers ranged a transmission line of the Consumers Power Company 40 miles in length, using a lightning generator capable of producing discharges of 1,500,000 volts. The generator was set up at one end of the line and the cathode-ray oscillograph was moved from point to point along the line. By comparing the shape of the recorded waves at various points along the conductor, the effects of travel on waves of various shapes were determined. Many different conditions were studied, which need not be mentioned here, although many of them are of considerable value to the designer of a transmission line. It was found, in general, that as waves travel, the fronts became less steep, and the tails longer. As an illustration of the dimensions of such a wave, a 1,000,000-volt 1.5 by 40 microsecond wave would have a front 1500 feet long, a crest or maximum potential of 1,000,000 volts and the voltage, after 40,000 feet of the wave had passed a given point of the line, would be 500,000 volts. We can make these measurements because electricity has the same speed as light, which roughly is 186,000 miles per second or (to express it in terms of the space it occupies on the trans-

mission line) approximately 1000 feet per millionth of a second.

Such waves travel along a transmission line without being seen, unless the voltage is high enough to break down the air around the conductor, resulting in a corona discharge. When this occurs at night, the momentary appearance of the corona, particularly if intense, may result in an appearance which some have called "ball lightning."

Having mentioned ball lightning, perhaps it might be worth while to digress at this point just long enough to take cognizance of that manifestation. Obviously the explanation given above will not at once satisfy all of those individuals who swear that they have observed a ball of fire float through an open window during a lightning storm, bounce along the ground, or perform similar acrobatics in their immediate vicinity. Man is extremely credulous, and in many cases probably does not actually see what he thinks he saw. Although ball lightning has been reported by men whose training is unquestioned, yet, there are certain limitations to the human senses which influence their observations.

Many people declare that they have actually seen what is called ball lightning. Not all of their descriptions agree, but most of them stress a certain spherical luminescence, indefinite in outline, and blue in color. It is usually associated with lightning storms, although some cases have been reported as occurring when no

storm was in progress. With these latter, we will be wise not to attempt to deal. Many observers also report the presence of the odor of brimstone.

In mentioning ball lightning we have attempted only to describe a set of reasonable circumstances which would produce such a phenomenon and at the same time explain it. We have never produced ball lightning in the laboratory, but we have never seriously tried, since it was not on our agenda. The persistence of vision is always an important factor when we consider any phenomenon relating to a light source. It is well known that the motion picture is not a moving picture at all, but a series of still pictures, with no picture on the screen during almost half of the time. In the lightning laboratory use is often made of persistence of vision, since often one cannot see the details of a discharge 30 feet in length at the time it occurs, but, as explained before, on the retina will be found a satisfactory image for study which will persist for several seconds. Other factors, besides persistence of vision, affect our observation and conclusions. It is well known that no two observers of an automobile accident will give the same report of what they saw. Even great care must be used when studying lightning photographs, on account of distortions and the fact that the camera sees only in one plane.

Dr. W. J. Humphreys of the United States Weather Bureau has studied all of the cases on which he could

secure data, and has satisfied himself that most, if not all, reported cases of ball lightning could be explained on some other basis. There is, however, some reason to believe that if ball lightning *does* exist, it is closely connected with the high stress at the surface of the earth which immediately precedes a stroke.

Returning now to our discussion of traveling waves, certain conditions must be understood to appreciate some of the simple relations of the traveling wave. As already explained, when lightning strikes a line conductor, a wave of potential travels away from the point struck in either direction. As long as the wave does not encounter any change in the conductor, such as a division in the line, a short circuit, an open circuit, or connected apparatus, the wave will continue to travel, undergoing certain gradual changes until finally the wave becomes so small as to be negligible.

However, we should not conceive of its simply going along and flattening out until it reaches zero magnitude and harmlessness, for transmission lines are not infinitely extended, and waves traveling along lines, as used today, may give rise to dangerous voltage at points considerable distances from the point struck.

This effect is the result of the reflection of the wave at a point where the line is open, as when a circuit breaker has opened, or when the line terminates in a piece of apparatus consisting of many turns of wire, as in the case of a transformer. Such a device impedes the

flow of the incoming wave so much that in a sense the wave piles up against the transformer, much as an ocean wave piles up against a concrete wall or breakwater. The mechanism of the traveling wave is such that when the wave can no longer travel, being blocked by an open line, the voltage wave at the very end of the line, as measured by a cathode-ray oscillograph, would be just twice as great as it would have been if the line had continued on indefinitely and the voltage had been measured at the same point. The wave shape would be just the same as before except all of the voltage values would be doubled. This means that the crest potential would be reached in the same time, but since the voltage would be twice as high, the steepness of the wave would be twice as great as it would have been if the line had not been open at that point. As an illustration, if lightning struck an unprotected transmission line at tower No. 20 and there was a flashover of the insulators at 1,000,000 volts, there would be a traveling wave moving away from tower No. 20 in either direction at the speed of light. Assume that in traveling a distance of twenty towers the crest potential decreased to 600,000 volts, which, when it reached the transformer at structure No. 0, would nearly double, becoming almost 1,200,000 volts, since the transformer acts almost like an open circuit for steep waves. If the station insulation were good for only 1,000,000 volts a flashover would occur, although no flashover would

have occurred on any of the towers between the point struck at tower No. 20 and the station. The other traveling wave moving on from tower No. 20 might have traveled far enough before reaching a terminal point so that its magnitude had become too small to be of any serious consequence. This illustration shows clearly the importance of protecting apparatus at the terminal points, since these are reflection points and higher voltages and steeper waves may be found there. It is only at points where the water stops that sea walls are usually placed to avoid damage to the property which the sea wall protects.

Everyone is familiar with the fact that if a stone is dropped into a pool of still water, circular waves will move outward from the seat of the disturbance toward the sides of the pool. If those sides are vertical, not only is the height of the wave increased at the edge, but a reflected wave will be seen traveling back toward the original source of the disturbance. If the stone is dropped in the center of a round pool, the reflected waves all converge upon the center and again continue to the edges of the pool. Finally, the waves will have quieted because of the frictional losses, and the original calm of the pool will be restored. So it is with the electrical traveling wave. After reflecting from an open end, the wave will be found returning, having its original wave-shape except for losses when it gets well away from the influence of the end of the line. Eventually

these losses will reduce the wave to zero, although several reflections may be required to accomplish this result. It is to be noted that the returning wave is positive if the original wave was positive, and negative if the original was negative.

Conditions are different, however, if the wave in its travel meets a short circuit to ground, which in service could be an insulator string which had suffered a flashover, or it could be a protector tube in operation, or some other protective device whose resistance at the moment was very low. To make the discussion as simple as possible, let us assume zero resistance to ground at tower No. 0, using the same illustration as before. The voltage at this point must be zero, since the product of zero resistance and the current flowing, no matter how large, must always be zero. However, this time the traveling wave upon reaching structure No. 0 will not be reflected with the same polarity as before, but with a reversed polarity. Thus a negative lightning stroke at tower No. 20 will produce negative traveling waves. The wave upon reaching the short circuit at structure No. 0 will not be absorbed, as one might expect; instead, it will be found that back from the short circuit, a sufficient distance to be out from under the influence of the end, the original wave will be found returning but having a positive polarity. If the original had been positive in polarity, the reflection would have been negative. In this connection it is interesting to real-

ize that there is nothing in the reflection in the water pool which corresponds to the reversed polarity reflection which occurs when traveling waves meet a short circuit.

One might suspect that if a short circuit caused the reflected wave to be reversed in polarity while an open circuit caused a reflection of the original polarity, some resistance between zero ohms and infinity ohms might result in no reflection whatsoever, and this turns out to be the case. For most lines this value of resistance is about 500 ohms, and if connected between line and ground will completely absorb the traveling wave with no reflections. It is also of interest to know that this same 500 ohms represents a special kind of resistance to the flow of transient current in a transmission line. In other words, to find the approximate current in a traveling wave it is only necessary to divide the voltage of the wave by 500 ohms. Thus, with the 1,000,000-volt traveling wave considered previously, there is a traveling-wave crest current of 2000 amperes. Such a wave, encountering a short circuit, would have zero voltage measured across the short circuit, but double the traveling-wave current, or 4000 amperes would be measured. After reflection, the current in the line with the traveling wave would again have become 2000 amperes, having the same polarity as the reflected traveling wave.

This matter of negative reflection is important in

protection problems, because the voltage, reduced to a safe value at one point on a line, is not necessarily safe at some other point. Thus, referring to tower No. 20 again, suppose that the towers are 1000 feet apart. Then, between the station at tower No. 0 and tower No. 20 there is a distance of 20,000 feet. It would take 20 microseconds for a wave to travel this distance. Thus, a wave starting to travel toward the station from tower No. 20 would not reach the protective device at the station for 20 microseconds, and it would be another 20 microseconds before the reversed reflection could return—making a total time of 40 microseconds before any help could be obtained at tower No. 20 from protection in the station less than four miles away. Thus, in stations, to be sure that the potential applied to a transformer due to lightning on the line is not more than the lightning arrester allows at its terminals, it is necessary that they be as close together as possible.

Distance is important with any wave phenomenon, and it was distance which rendered ineffective the lightning protection of a very tall statue in South America in Rio de Janeiro. This statue, which was 120 feet in height, was built of soapstone over a framework of metal. The outside of the statue had a properly installed lightning rod system. It was found that during storms, which are frequent in that part of the world, discharges were passing through the statue from the outside lightning rod system to the supporting metal

framework. The reason why the protection was ineffective is contained in our discussion of traveling waves. When lightning struck the outside rods the voltage began to build up higher and higher as the traveling wave passed down the rod. Finally, after traveling 0.12 microsecond, the wave reached the ground, and the reversed reflection began to climb up the rod, taking 0.12 microsecond to reach the top. No reduction in potential could take place at the top until this reversed reflection returned. During that time interval of 0.24 microsecond, the potential at the top had become high enough to penetrate the soapstone and make connection to the supporting steel. The solution was to connect the inside steel work and the outside protection system together at several points, and this stopped all the trouble.

We are surrounded by waves of one sort or another —light, heat, sound, and radio—and now we find that electrical disturbances travel over wires in the form of waves. In the case of lightning the effects may be destructive, but we may also find them very useful, since our telephone conversations are carried over wires and they too obey the laws of traveling waves.

9. HITS AND MISSES

IT IS a highly dramatic moment in nature when lightning rips out of the sky, picks its target, and strikes—and we are susceptible to the dramatic, being human. Yet, if conditions are right, lightning need not strike directly to cause voltages to appear between conducting objects. Voltages appear in overhead wires by a process called induction when strokes take place near by, even though the wire is not struck. This was well illustrated by the case of the man who lived in a cottage on a hillside and who used to amuse himself by watching sparks jump between the faucet and the sink during storms—a practice, by the way, which is not to be recommended. The faucet was connected to a spring by a long pipe lying on top of the ground. Such a pipe

may be a source of dangerous voltages by the process of induction as well as from a direct stroke to the pipe.

To the amateur lightning hunter, as well as to the professional, a knowledge of this "indirect stroke" is necessary if he is to understand how one can receive a shock without being struck. We know how a sizeable voltage suddenly appears on a transmission line struck by lightning. It can also appear when the lightning discharge is between one cloud and another, or between cloud and ground, when the transmission line itself has not been directly struck at all.

This action may perhaps be best understood if one will imagine a storm cloud floating along above the earth. In the lower portion of the cloud, negative charges have accumulated because of the thunderstorm action, pushing the positive charges into the upper region of the cloud. Underneath, in the earth, is found a similar collection of positive charges induced by the negative cloud charges, and these are said to be "bound" to the negative charges overhead. The negative charges in the cloud have an attraction for the positive charges in the earth, since charges of the opposite sign attract each other. And because charges of the same sign repel each other, the negative charges that were in the earth before the advent of the thundercloud find it imperative to move away from the spot in question. As the charged cloud drifts along, it pulls these charges of opposite sign in the earth along with it, even as a cloud's

shadow follows it across a field with the sun directly overhead.

Now let us consider that a long conductor, or transmission line, extends across the field. Part of it is in the area directly underneath the cloud, and is therefore subject to the same influences as the earth. In other words, positive charges in the conductor also are bound to negative charges in the cloud, while the negative charges which were formerly in the conductor—before the cloud came along—move away in either direction, repelled by the negative charges in the cloud overhead.

If the cloud field were so large in area, the line being relatively short, that the latter were entirely contained in the area beneath the cloud, a similar condition would still ensue. This is because most overhead conductors are imperfectly insulated, and all of them are necessarily closer to the cloud than is the ground itself. In these circumstances, positive charges from the ground will move up into the line leaking slowly over the surfaces of the insulators. The pull on them, exerted from above, is so strong that they will climb as close to the cloud as possible.

This action of redistribution of electrical charges (in cloud, conducting line, and ground) has plenty of time —a matter of seconds or longer—in which to take place, and the positive charges on the conductor can become bound to the negative charges in the cloud in the same

manner as the charges in the earth beneath it have become bound.

With the stage thus set for action, let us suppose that a lightning stroke occurs between cloud and earth. The stroke allows some of the negative charges in the cloud to unite with some of the positive charges in the earth at the point struck. This causes a reduction of the strength of the electrostatic field between the charged cloud and earth underneath, and some of the bound charges in the transmission line are set free. This results in a movement of these released positive charges out of the cloud field, which in turn results in waves traveling along the line away from the cloud field. These released charges cause a positive potential (voltage) to appear on the line, one which could be measured by an oscillograph in the same way that the effect of a direct stroke to the line is measured.

The conductor, as a result, undergoes the same kind of experience that it would have undergone if it had been struck by lightning; yet it was only an innocent, unstruck bystander, *the victim of an indirect stroke*. It is important to note that the charge released on the line always bears the sign opposite to that of the charged cloud. Thus, if our instruments show a positive traveling wave on a line, and we know that the direct stroke was from a negatively charged cloud, we immediately know that the traveling wave was caused by the release of a bound charge on the line. By this means we could

identify the indirect strokes, providing the polarity of the discharging cloud were known.

For many years prior to 1928 it was thought by engineers that the indirect lightning stroke (induced voltage) of the kind just described was responsible for much of the trouble experienced on transmission lines during lightning storms. It remained for certain investigators to disprove this theory, with the result that later attention was focused on the direct stroke. C. L. Fortescue, a Westinghouse engineer, showed that the induced voltage was not of serious consequence on high-voltage transmission lines on account of the time taken for the stroke to complete its path; thus the change of cloud field was not instantaneous. Before him, Peek had estimated that the potential produced under these circumstances approximated 100,000 volts for each foot of height of the transmission line above ground. But it was shown that a certain length of time was required to establish a connecting path between cloud and ground for the stroke, perhaps 15 microseconds or longer. This is a long time in the life of a voltage wave. It is obvious that if a cloud field changes its character slowly enough, the bound charges will be released—not in zero time—but slowly also, and as they are released they will trickle out along the line. The potential then developed at any one time is much smaller than might be expected. At this point the reader will note with some curiosity that we have progressed

in our thinking to the point where we can speak of the "slowness" with which lightning strikes. Men live for decades, flies live for weeks, and lightning often lives in millionths of a second; yet each time span is sufficient for an appointed number of tasks to be performed.

Still another reason why a transmission line may not be disturbed unduly by an indirect stroke is that often only a small portion of the cloud will discharge at any one time. The distance from cloud to ground is also a factor here, as a certain length of time is needed to complete the lightning path to ground even in a uniform field. This was first determined in the lightning laboratory by J. J. Torok, who demonstrated that time was required to break down the air between two spheres so that the lightning discharge could pass. This served as additional evidence of the importance of studying the direct stroke. In any case it was necessary, in determining indirect effects, to know the rate at which the cloud field changed, and this was again dependent upon the mechanism by which the direct stroke was formed.

Isolated conducting objects (metal projections in the air such as an ungrounded metal roof) may become the center of considerable unpleasant activity in such a collapsing cloud field as we have been discussing. If these objects are separated from a grounded conductor (pipes or wires) by a small gap, they may develop sufficient potential from the indirect stroke to cause a

flashover at the gap. It is important that a lightning rod system be well grounded. Cases are reported occasionally where a small gap has existed between the down lead and the ground connection and sparks were observed to jump across even though the building was not struck at the time. This is a good demonstration of the release of a bound charge in the lightning rod conductors manifesting itself in sufficient voltage to jump across a small gap. Needless to say, such a gap should be properly closed. The same situation exists in buildings in which are inflammable gases or explosive dust, if large conducting bodies are insulated from, but close to, grounded objects. Due to sudden changes in cloud fields during lightning storms sparks may jump the gap and cause an explosion. The fact that the large metal body is inside a building does not avoid the induced potential unless the building is of metal frame construction—but this will be discussed in greater detail later.

At this particular period of lightning research, several investigators began turning up results with field equipment. In South Africa, Dr. B. F. J. Schonland first studied cloud fields and later the mechanism of the stroke itself. During the summer of 1928 three cathode-ray oscillographs were installed in the United States, each being coupled to a transmission line for the purpose of capturing the wave-shapes of traveling waves due to lightning, whether induced or direct. One of these oscillographs was located at Chilhowee, Tennes-

see; another at Wallenpaupack, Pennsylvania; and the third was located at Croton Dam, Michigan. Quite a large number of oscillograms were obtained, particularly at the Wallenpaupack installation, and although much useful information was gathered, none of the strokes measured struck close to the waiting oscillographs, but many did strike the conductors at varying distances along the line.

At the same time Harald Norinder in Sweden, and K. Berger in Switzerland, reported the recording of more than 100 surges caused by lightning. The lightning hunters were active on several fronts, comparing notes. While one oscillograph was set up at Cherry Valley in Pennsylvania, coupled to the 220,000-volt transmission line of the Pennsylvania Power and Light Company, a direct stroke occurred (July, 1930) to the line at a point not more than 500 feet from the instrument. It was an occurrence which most individuals would have been glad to miss, but the engineers in charge congratulated themselves on the resulting oscillogram, which was a valuable addition to the "bag," even though the near-by insulator flashed over, cutting off the "tail" of the wave. However, the shape of the front was obtained, and it was found that the crest voltage at the point where the record went off the film was 2,700,000 volts. In the same period, to give another example of field experience, an oscillogram was obtained (on a transmission line of the Arkansas Power

and Light Company) of a traveling wave caused by a stroke four miles away. It flashed a distance of 22 feet from the line conductor to a telephone line on a lower level. The oscillogram indicated a voltage of 5,000,000 volts at the crest of the wave; the whole performance lasted 50 microseconds. Eight cathode-ray oscillographs and two portable lightning generators, rated 1,000,000 volts or more, were in service in the field during 1929.

Because of the great cost involved in catching lightning wave-shapes by the tail, as it were, where an oscillograph was employed, and because of the uncertainty as to the wave-shape at the origin of the stroke, this type of investigation was discontinued in this country after 1930. Some practical results had been obtained, however. The conviction grew that a better ground had to be provided for transmission towers if the overhead ground wire was to prevent insulators from flashing over when lightning struck either the towers or ground wires. The resistance of the ground had to be lowered, and two methods were available. One was to drive more and longer ground rods. The other was to bury a type of conductor, called a counterpoise, in the ground to a depth of from one to three feet. If the towers were connected together in this manner—below the ground—this was called a continuous counterpoise. If the underground conductors were extended at an

angle from the overhead line (usually 45 degrees), they were known as a radial counterpoise.

The first continuous counterpoise installed as a result of these investigations was in 1929. It was approximately three miles in length and was connected to the base of each intervening tower of the 220,000-volt transmission line. Before the installation, the line suffered 29 flashovers in three years. During the next seven years, after the installation of the counterpoise, this section of the line had no flashovers, indicating some measure of success in protecting the service against interruption due to lightning. In 1931 radial counterpoises were installed for a distance of four and one-half miles on the same line. During the following six years only one interruption occurred due to lightning on this section of the line.

As indicated before, the oscillograph was yielding too little information for the expense involved, and a less expensive telltale was needed, one which would indicate the current in the direct lightning stroke. An answer was found in the magnetic link.

It had long been known that lightning currents would magnetize magnetic materials, and this principle was called into play in 1932. The link, consisting of a few strips of cobalt steel, about two inches long, enclosed within a tubular molded container of suitable magnetic material, was attached perpendicular to the conductor in which lightning current was to flow. In

practice the link is tested after each storm with a simple indicating device, and if the link has become magnetized, the patrolman brings it to a central point where the degree of magnetization is determined by an instrument called the surge-crest ammeter. From this a direct reading of current can be obtained.

The first results from this comparatively inexpensive and simple device were reported in 1934 by W. W. Lewis and C. M. Foust, and they showed that lightning currents in the transmission towers studied ranged from 4000 amperes to 63,200 amperes, with a cloud of negative polarity indicated in practically every case. This meant that the top of the transmission tower was positive with respect to the cloud, a simple and generally accepted statement today, but one which had to be definitely established.

Electrical transmission lines are a commonplace to our civilization. At least by implication, each one of us —no matter how uninformed he may be—knows that they exist for the purpose of bringing to our homes and factories the vital energy to turn wheels, light lamps, and perform the thousands of functions which animate modern life. But we accept such things without stopping to inquire by what means they perform their duties so effectively, hardly being aware of their presence until they suddenly become ineffective; then our dependence upon them is realized. Much like the skin which covers our bodies, we are conscious of trans-

mission lines only when there is pain or a default of some kind. Yet these same, seemingly endless overhead wires, have been the means of providing us with a host of creature comforts. To the lightning hunter they have also been invaluable in serving as a laboratory table, upon which the lightning stroke has been dissected a little at a time, and many of its habits and characteristics laid bare.

After another year of placing, collecting, and testing magnetic links had passed, our researchers were able to draw certain conclusions. They could say that a counterpoise (buried ground wire) served effectively to reduce the resistance to ground at the base of a tower; which meant that the flashover of insulators, and consequent interruption to service, could be prevented in a large measure, provided the line was equipped with overhead ground wires. They knew that the surging currents of direct lightning strokes on a tower or supporting structure would range from 2000 to 150,000 amperes, and that they should therefore build structures to withstand the severe conditions imposed by lightning. They knew that probable stroke currents would range from 2500 to 220,000 amperes. From the telltale links they knew that in two years 97 per cent of all direct lightning strokes to the transmission lines studied had been from negative-polarity clouds. Finally, they knew that in a territory having an average of from 30 to 40 storms per year, 42 strokes for each 100 miles

of transmission line could be expected on the average.

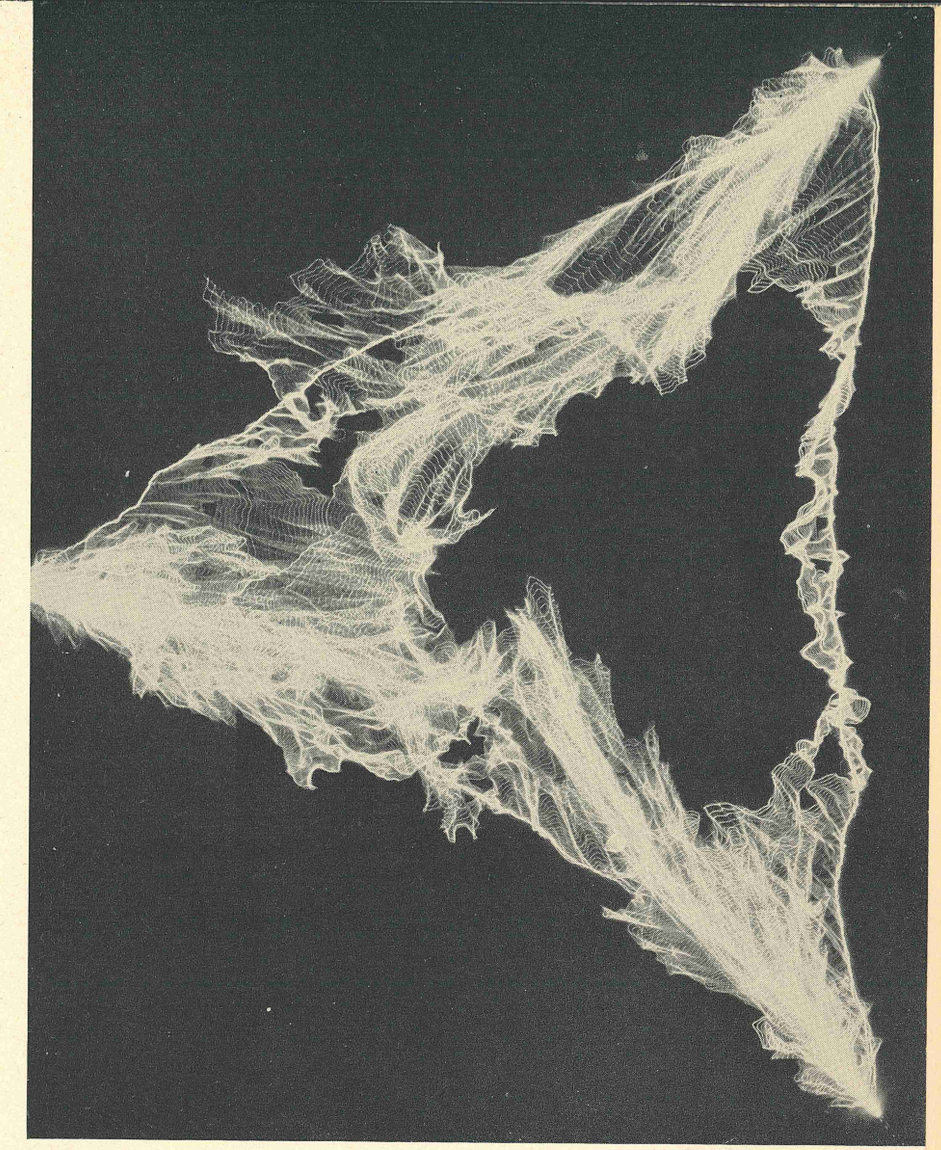
Any research into natural phenomena is necessarily a pedestrian activity. It lacks bounce, verve, color—and its adventures come to pass painfully and slowly. Even in retrospect it is difficult to knit the story of lightning study in the field into a well-timed and conclusive account. The magnetic link constitutes a stiff and unresponsive hero for our romance until he can be induced to give up his secrets and they in turn are interpreted. The cathode-ray oscillograph, while of a delicate and high-strung nature, lacks the blush and pulse-rate of a conventional heroine. We who have called them onto the stage must perforce let them speak their own lines, in their own good time. They will not be hurried. In the ensuing pages it will be our more pleasant duty to hold both the microscope and the mirror up to the sky-born bolt.

10. INDOOR THUNDERBOLTS

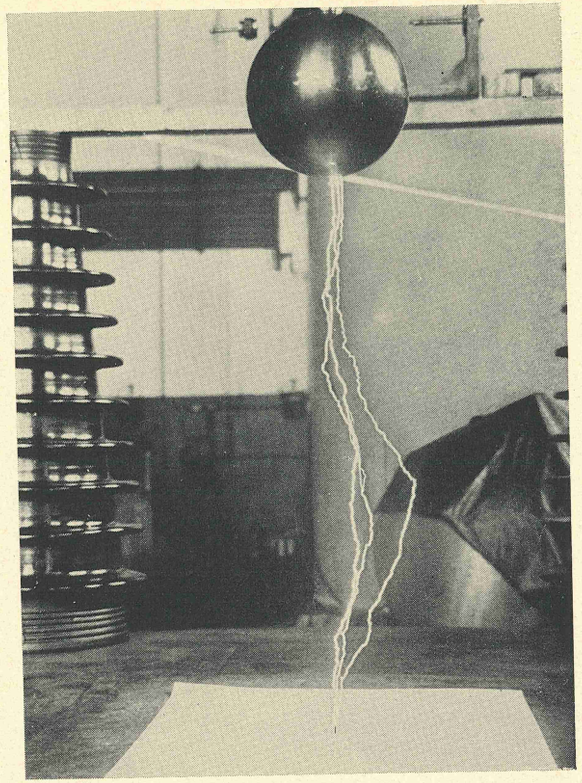
IT IS apparent that in one sense all outdoors has been the laboratory for the lightning hunter. However, much valuable information has been gained from working with the more controlled factors which we have been able to produce under a roof. Its value lies principally in the ease with which measurements can be taken and the artificial thunderbolts manipulated. After all, the outdoor lightning season is rather short, and may be singularly unproductive of results. Every day is midsummer in the laboratory, yet it never rains. When, in 1932, there was added to our indoor equipment the lightning generator capable of producing potentials of 10,000,000 volts and lightning strokes 30 feet long, we were able to study the effect on electrical ap-

paratus under conditions very close to those encountered in actual outdoor service. The voltages we produced were actually higher than those which generally appear on transmission lines during storms as a result of natural lightning.

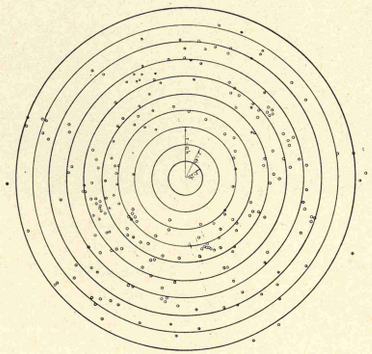
Measurement, which dogs the research man's footsteps constantly, is more than ever the theme song in the high-voltage laboratory, and some queer-looking yardsticks are employed in the process. Perhaps the most familiar is the sphere gap, promulgated many years ago by Peek, as a proper means for correctly determining 60-cycle voltages. Probably the only reason that sphere gaps are familiar to the layman is that they are usually prominently displayed in the scenes of movie thrillers which are supposed to take place in the deserted laboratory of a maniacal scientist. They seem to support an eerie, Wellsian atmosphere, comparable as a thrill-producer to the buzz saw and the powder house of our youth, in which the heroine was bound and gagged. Sphere gaps in themselves are quite harmless, however, unless they happen to be connected up to an artificial lightning generator or other electrical source. As their name implies, they consist simply of rather large metal spheres, properly supported, separated by an air gap across which an electric arc is made to jump. The distance which the arc jumps is substantially the measure of its potential, and the spheres are moved closer together and farther apart during the



Time exposure taken from above of a 1,000,000-volt three-phase 60-cycle arc between points separated 108 inches. Note changing path as discharge rises. Fine lines result from alternating potential changing polarity 120 times per second.



Laboratory lightning striking a miniature rod to determine the protected area around rod. Tests by F. W. Peek.



Record of strikes to plane surface with one-half-inch needle-point at center of circles. Cloud (represented by sphere) is directly over needle. There are no strikes within an area whose radius is equal to four times height of needle.

process, determining just how much distance an unknown voltage will jump. Measurement of the gap length determines the unknown voltage. The air space between two spheres constitutes the dielectric field, which must become stressed and eventually broken down before the arcing can take place. The spheres are so shaped and located in the laboratory that the dielectric field is approximately uniform throughout. During these measurements it was discovered that this dielectric strength (of the air) was influenced by both atmospheric pressure and temperature, i.e., by air density. For laboratory purposes, these factors are measured carefully during tests, so that the proper correction factors can be applied.

Although the sphere gap is usually recognized as the standard measuring device for such purposes, other types of gaps were used. One was the needle gap, in which two needles of specified shape were supported, point to point (except for the gap) along the same axis. Another type was the rod gap, made from a square section rod cut off square at the ends. The rod gap and the needle gap are sensitive to humidity as well as to air density. Laboratory lightning voltages are also conveniently measured with a cathode-ray oscillograph, whose deflections have been previously calibrated.

Since most electrical apparatus consists of copper conductors which are properly insulated from iron or steel parts by a solid, a liquid, a gas, or a combination

of these things, it is important that we know the strength of such insulation when exposed to lightning attack. Lightning is a fast-moving phenomenon, as has been demonstrated in the preceding pages, increasing and then decreasing its voltage much more rapidly than does the 60-cycle current which is generated for household use. We have discussed lightning waves, and have noted that they rise to their peak voltage and decay in a very few microseconds, whereas the 60-cycle wave requires 4166 microseconds to rise to its peak, and then it decays at the same rate. Much of the time of the laboratory men, employing the lightning generator and the various measuring devices, has been devoted to this extremely practical matter of how much voltage, rising and subsiding in a given time, will flashover, break down, or otherwise damage the various types of insulations.

The spheres or rods constitute the two electrodes of the gap across which the discharge passes, just as the cloud and the earth are the electrodes for a natural lightning flash to ground. It has long been known that the *shape* of these electrodes had much to do with the amount of voltage required to flashover a given air gap. The highest voltage needed to accomplish such action was when the electrical stress was substantially uniform, as it would be with very large spheres or with opposing surfaces which were shaped like doorknobs. In such cases the point at which the flashover takes

place has very slight curvature. Calculation, supported by laboratory tests, showed that such a surface, approaching flatness because the radius of curvature is so small, avoided the concentration of stress at the electrodes which would start a progressive breakdown of the air.

On the other hand, if one electrode is sharp, as is a needle point, the other electrode being flat, then the voltage required to flashover is much less. This is particularly true if the needle point has a positive polarity, and then of course the flat surface is negative. Similarly, with a lightning storm in progress overhead, a flat field would be struck in a hit-or-miss manner, but a tree or steel tower, usually having a positive potential, would guide to itself the discharges which otherwise would have taken place over a considerable area. Sometimes, the actual height of the structure is increased by the presence of streamers extending upward toward the cloud, which assist in guiding the stroke to the elevated object.

Before his death, Peek made a number of interesting tests with models representing buildings at which artificial lightning bolts were discharged. These tests, however, did not discriminate with respect to the polarity of the impulse. In one of them a large sheet of paper or cardboard was placed on the laboratory floor, and a spherical electrode hung several feet above it, in the position that a thundercloud might assume if it were

stationary. Circles were drawn on the paper, and at the center was erected a vertical pointed rod, designed to represent to scale a metal mast or pole extending above the surface of the earth. The "cloud" was then caused to discharge artificial lightning bolts in the direction of the paper. Employing this arrangement, Peek found that there was an area surrounding the rod in which the discharges did *not* strike, but instead the rod was struck. This inviolate area, circular in shape, had a radius four times the height of the rod itself.

To find the effect of cloud height and position, Peek moved his artificial cloud around in different locations. He found that when the cloud was not directly over the pin, the latter's protected area could be found by projecting a circle whose center was the cloud and whose radial limit just touched the top of the pin. Where the circumference of this circle struck the paper, marked the boundary of the protected area. This really says that the nearest object will be struck. This is reasonably true, probably for points near the earth's surface, but the cloud ends of strokes sometimes do considerable wandering around—but more of that later on.

This "cone of protection" was not an entirely new conception, because a similar theory had been described many years before in a book written by Sir Oliver Lodge, but Peek, because of the equipment he had available, was able to give it substance. It is hardly necessary to point out that the proper determination of such a

protective cone is highly important, because it is the basis of many lightning-protection installations today.

Additional work on the cone was carried out later in Schenectady, and the findings reported by Lewis and Foust indicated that there was a considerable difference in the size of the protected area when the cloud was known to be negative in its polarity and when it was known to be positive. With negative polarity, the protected area fell within a circle having a radius roughly ten times the height of the structure, instead of four times, as in the Peek experiments.

There is, of course, considerable doubt as to how accurately such laboratory data can be applied to actual conditions out of doors, but from practical observation the protective-cone theory seems to be approximately correct. In the laboratory the discharge may be only 10 or 15 feet in length, while outdoors it may be from 100 to 500 times as long. Also, the conditions in the cloud preliminary to and during the discharge are impossible of exact duplication, and this may have some effect in changing the ratio of structure height to protected area. Some of the results obtained while watching natural lightning strike in such an area with a protecting tower will be disclosed later. In the construction of transmission towers, we usually use a cone whose base radius is twice the height of the tower.

In another demonstration Peek showed in the laboratory how a wood pole in a dry and substantially non-

conducting state would not be struck by the artificial lightning discharges, while a metal rod placed within the cone of protection of the pole would be struck. However, when he made the wooden pole slightly conducting (as it would be when wet or if it were a green tree) the discharge would strike it, providing the metal rod were within its cone of protection.

In another set of circumstances, duplicating possible natural conditions, even though the metal rod was much lower than the wet wood pole—but was now placed close to it—the discharge would begin by striking the "tree" and then side-flashing to the metal rod.

These tests clearly illustrate what happens when a natural lightning bolt strikes a tree and then jumps to a near-by house containing grounded metal objects, thus finding its way to ground. In such a case—and there are many of them—the resistance of the tree, because of its moisture content, to the flow of electricity is high enough so that sufficient voltage exists to jump from the tree to the near-by grounded object. Incidentally, such a "grounded object" might just as easily be a human being, and that should be a sufficiently good argument against standing under a tree during a thunderstorm.

Peek's work was extremely valuable in pointing out the proper measures to be taken for the protection of oil and gas tanks and ammunition dumps. The protected area plan was adopted for the safeguarding of oil storage tanks in Southern California specifically. Several

tall rods, placed near the outside of the big oil reservoirs, provided overlapping protected areas and greatly reduced the hazard of conflagration from lightning flashes. He also demonstrated that isolated conducting surfaces should not be allowed to remain without bonding (i.e., connection) close to other metal surfaces which might be grounded, when inflammable vapors were present. To those who have followed the preceding chapters, it will be obvious that in such a case lightning would not have to strike the isolated metal in order to cause trouble. Our old friend, the indirect stroke, could easily be the villain of the piece. Sufficient voltage might be *induced* through the release of bound charges at the time of a stroke near by to cause a spark between the grounded and the isolated metal. Then the vapors present would take over the situation with probably disastrous results. Such a hazard can be eliminated by bonding the two pieces of metal together.

Thus, at some length, have we established the relationship between an oscillographic curve and the hapless individual who takes shelter beneath a tree during a thundershower. It might be a good thing if the man and the curve would make each other's acquaintance. Lightning is not averse to striking more than once in the same spot—but frequently once is sufficient.

11. GUNPOWDER OF THE GODS

PRESSURE plays an important part in our lives. Like force, it marks the difference between a caress and a concussion, and that is indeed a great difference. The work done by a force is a matter of speed, or of the shortness of time in which a given force acts. If a baseball bat is moved gently in an arc by one player towards the skull of another—say, at the rate of an inch every ten seconds—no damage is likely to result. But if that bat is swung with all the speed and force which a home-run hitter can command, the result is not pleasant to contemplate. Perhaps this is a good point at which to hark back to the curve or wave-shape of a lightning discharge, and endow it with a realistic quality which may have been lacking in the previous discussions. A

curve could be drawn for the bat which moves slowly—it would start at zero and rise very gradually as the bat increased its speed from nothing to a tenth of an inch per second. Another curve could be drawn for the swiftly moving bat, also starting at zero and reaching its peak quickly; its rate of ascent would be very steep, and the peak would represent a broken head. Lightning strokes, in the parlance of baseball, are home-run swings; the steepness of the front of the wave reflects accurately the speed with which the voltage, or current, builds up.

The passage through the air of an electrical discharge, such as lightning, causes a pressure to be developed which is dependent upon the amount of current in the discharge. This pressure may reach its full magnitude in as short a time as five millionths of a second, or perhaps even less, and produces many of the damaging effects associated with lightning. It is the cause of the thunderclap accompanying the discharge. It is the cause of the physical tearing and rending which may occur when a wooden building, tree, or pole is struck. If moisture is present, as it is in the case of a growing tree, the resulting vaporization will add to the pressure developed. The current in a lightning discharge varies between wide limits. It may be of the order of 1000 amperes or less, or upward to 200,000 amperes.

One of the first effects of lightning to attract the attention of the lightning researchers was that of the shattering of wood. It was one of the earliest experiments

tried by Steinmetz, and has since been repeated many times on a much larger scale with the laboratory discharge. A characteristic effect, found both outdoors in trees and poles and indoors in laboratory samples, was the channel created by the passage of the discharge, where a certain amount of wood had been vaporized. Examination showed that the wood had been blown apart because of the pressure developed in and around the discharge path. We have said that this pressure comes from the current involved, and the rate at which that current builds up pressure. In other words, it comes largely from heat generated. The larger the current flow, the greater the heat effect and the more violent the disruption of the wood. The violence itself is some measure of the *rate* of current increase.

The effect of the rate of release of a given amount of energy can be well illustrated with gunpowder. If the powder is unconfined in an open dish on the laboratory table and a match is touched to it, all that results is a certain amount of flame and smoke. There is no serious explosion. But, if the same amount of gunpowder is confined in a metal chamber of such strength that the chamber bursts as the pressure within approaches its maximum, then we may lose the windows and a good portion of the walls of the laboratory. Certainly the table will not be worth picking up, even if we can find it. We have created an explosive bomb.

Why this difference in effect with the same amount

of energy? The answer lies in the very *steep* wave of pressure which moved out from the exploding metal can and was fully capable of doing the damage we have indicated. The amplitude of the pressure wave was very high. It is quite likely that no fire would result from the confined explosion, whereas there might be considerable danger of fire from the slow-burning unconfined powder. The physical damage was done by the high pressure. With a small amount of energy the only way to obtain high pressure is to create a very steep rate of rise. So it is with either outdoor lightning or the laboratory variety. In both cases the energy is limited, but the rate of application may be very high.

The foregoing calls for a brief consideration of energy and horsepower, or, in electrical terms, kilowatt-hours and kilowatts. When we pay an electric bill we pay for energy we have used, or for so many kilowatt-hours, and a kilowatt-hour is simply the use of a thousand watts of electrical energy for an hour, as registered on your meter. This energy represents work done in operating motors, lighting lamp bulbs, or creating heat for such appliances as toasters and flatirons. The rate at which the work is done is expressed in kilowatts. If we have a motor requiring three kilowatts for its operation, and we run the motor two hours, the total energy used is six kilowatt-hours. But if it had been possible to run that motor for one second, or for a mil-

lionth of a second, the energy input would still be at the rate of three kilowatts.

Turning now to the two 5,000,000-volt lightning impulse generators of our Pittsfield laboratory, let us see what they have to offer in the way of energy. These may be connected either in series, or in parallel, as desired. The total energy stored in these two Pittsfield generators together is but 125,000 watt-seconds. Since the ratio of watts to kilowatts is 1000 to 1, and the ratio of seconds to hours is 3600 to 1, we can easily calculate that the total stored energy in our artificial lightning machine is only 0.035 kilowatt-hour. Compared to the six kilowatt-hours we discussed previously, this is almost nothing. At a cost of five cents a kilowatt-hour, the stored energy in the impulse generator can be purchased on the market from your utility company for one and one-half tenths of a cent.

Yet observe what happens when a little more than one-tenth of a cent's worth of electric energy is released in eight millionths of a second. If you care to perform a little more arithmetic (multiply 125,000 by 1,000,000 and divide the product by 8×1000) you will discover that the lightning generator is releasing its energy at a rate of 15,625,000 kilowatts on the average. This is more than the average power generated by all the power stations of the United States during the year 1937. In effect, we have power equal to that produced by all the power stations in the country working for us

for those eight microseconds, and it is little wonder that so small an amount of energy can do so much damage.

Although the 10,000,000-volt lightning generator has served both to frighten and to delight the public in its numerous formal appearances, it does not represent the last word in destructive technique that we have been able to produce in the laboratory. That honor is reserved for another piece of apparatus, a true vessel of wrath, which will be described here. It is a high-current impulse generator, constructed in 1934 in order that we might pursue further a certain line of investigation. It is greatly to be doubted that this apparatus will ever make its bow at a world's fair or other exhibition, partly because of its nasty temper (it has a penchant for hurling debris at spectators) and partly because the 10,000,000-volt generator puts on a more spectacular performance, with its 30-foot arc. As is the case in prize-fighting, however, where the short and unseen punch does far more damage than the long blow visible to the gallery, the high-current generator really packs a wallop. The efforts of newsreel photographers to capture its interest on film have never been successful, although the experience itself proved exciting enough. One cameraman in particular, who had taken refuge behind an iron screen, had his professional calm shattered when a block of wood was violently propelled through the screen itself, missing his head by barely an inch.

But, as the reader may suspect, the lightning generators are not built with an eye to their public appearances. The latter are quite incidental to the task at hand. Although the 10,000,000-volt generator, when reconnected in series-parallel arrangement, would deliver a current of more than 50,000 amperes when charged to capacity, yet such high-voltage generators are not convenient for many types of investigation. Furthermore, tests useful in the study of natural lightning had to be made with current values of the order of 200,000 amperes.

The Pittsfield high-current impulse generator built in 1934 had an open circuit voltage of 150,000 volts, with a capacity of 5.33 microfarads. When reconnected to give 50,000 volts, the capacity was 47.97 microfarads and it was capable of delivering on short circuit a maximum current of 265,000 amperes. In building such a machine, the length of the circuit, including the piece to be tested or struck, must be kept very short, so as to keep the inductance to as low a value as possible. The inductance is the most important factor in limiting the maximum current to be obtained. Its effect was kept low by arranging the capacitors in a hollow square, each of the 32 parallel-connected groups of capacitors being connected to a common conductor in the middle, much as spokes are connected to the hub of a wagon-wheel. The piece to be tested was then inserted in this central conductor.

With the high-current impulse generator most of the work done in the laboratory was directly associated with the effects of lightning upon electrical apparatus, and particularly with the destructive effects of high currents. One of the first things to be discovered was the extraordinarily loud report resulting from a high-current discharge in the air. Laboratory workers who had grown accustomed to our earlier brand of "thunder" were forced to cover their ears when the new apparatus discharged. The total energy involved was about the same as for the other generator. From the spark there also emanated a pressure-wave which would rock bystanders back upon their heels, and could be felt effectively on the chest 30 feet away. These characteristics, in addition to the aforementioned flying debris—bits of wood, metal, and concrete—made it necessary to house the test piece inside a box made of two-inch wooden planks. This procedure increased our comfort and safety considerably.

One of the lightning phenomena that had been reported from the field was the crushing of hollow conductors carrying lightning current following a stroke. It had been pointed out that this was caused by the magnetic effects of current flowing in the same direction on opposite sides of the tube, or hollow conductor. If this current is sufficiently large, the magnetic forces become great enough to crush the tube.

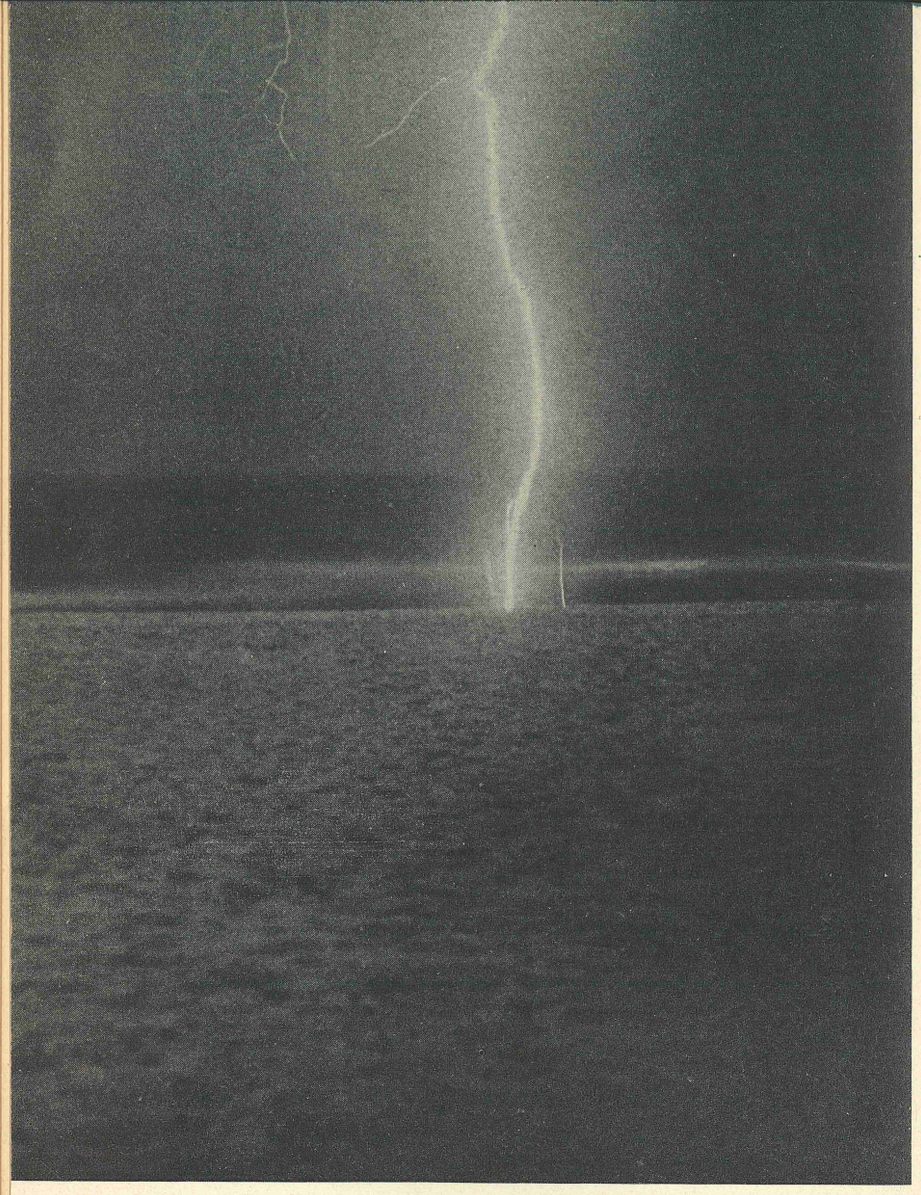
We made a test accordingly on a flat strip of copper

an inch wide and a few mils in thickness. The strip was crushed by the passage of a discharge from the high-current generator. The appearance of the strip indicated that the passage of the current had heated the metal considerably, which made the job of crushing a little easier for the magnetic forces.

Another strange bit of electrical magic, which was frequently reported by men operating outdoor telephone circuits which had been exposed to lightning, was that the metal conductor would disappear completely during a storm without any apparent damage to the rubber insulation. In other cases the rubber might be slit open; in still other cases nothing would remain of either the insulation or the wire.

With the high-current generator, we tested pieces of No. 14 rubber-covered copper wire, a type of conductor commonly used in the past for house-wiring. We found that by properly adjusting the current in our laboratory lightning generator, we could reproduce these effects. The conductor could be made to vaporize. In some cases the rubber would be split open, while in others the insulation would appear to be unharmed. No doubt an analysis of the rubber would have disclosed some of the missing copper. It is of interest that the copper was heated beyond its melting point by the discharge, yet the rubber insulation did not catch on fire, which again indicates how quickly the removal of the metal must have taken place.

What happened to a No. 25 nichrome wire when current from a 5,000,000-volt generator was passed through it. Current must be adjusted carefully to give this effect since too much current eliminates wire without shower of sparks seen here.



Lightning striking New Jersey beach 100 feet from camera. Preceding completion of stroke, streamers formed from beach and built upward as downcoming leader approached. Forked streamer on right was about six feet long and one on left four feet long. Downward leader evidently made contact with third upward streamer at a point about eight feet from ground. Upward streamers disappeared when return stroke was established. Photograph taken August, 1934. Courtesy Ewing Galloway.

Iron, copper, and aluminum wires approximately one-eighth of an inch in diameter could be fused with this high-current discharge. In the case of the iron wire, the sparks were thrown more than 30 feet, which may have some bearing on a report that came to us on one occasion when the Empire State Building in New York City was struck by lightning and observers saw a shower of sparks. This effect was nearly absent with copper or aluminum wire.

Of less scientific interest was the laboratory trick of directing the discharge at old framed pictures which hung on the wall. The nails holding the frame together would be fused and disappear, and the separate pieces of wood and glass would crash to the floor.

Another beautiful effect simulating Niagara Falls can be obtained by discharging the 10,000,000-volt generator through a piece of nichrome wire. It is to be suspected that this is what a radio antenna may look like sometimes when it is struck by lightning.

Having illustrated, by this brief excursion through the laboratory, the important part played by pressure and the rate of current increase in rounding out the destructive effects begun by the lightning discharge, and having made the reader familiar by means of laboratory devices with what takes place in nature, we may again take to the outdoors to examine more closely the stroke itself. In this task the camera will prove to be invaluable.

12. DISSECTING THE LIGHTNING STROKE

PERHAPS we have now arrived at a point in this narrative when we can figuratively extend our hand, grasp a bolt of lightning by its tail, and pin it down to our laboratory examination table for closer observation than has been possible heretofore. Snatching the bolt is not enough, of course, for we must inspect likewise the cloud and the earth, both of which take an active part in the strokes which land in your back yard. In previous pages we have rather hurriedly passed over the stroke itself for obvious reasons. A certain understanding of the tools used in lightning study and a short discussion of the physical behavior of electrical currents were first needed to prepare the way. Now let us see just what are the actions involved in the birth and brief

career of lightning, our volatile biographical subject.

We will attempt no explanation of the thunderstorm itself, for it is safe to say that there is no single theory to which all scientific men subscribe. No one has been able to put his finger definitely on the great secret of organic life, either, but that does not discourage the doctor of medicine from pressing the search for knowledge in both directions, toward death and back toward the genesis of human beings. In the same spirit let us begin with the thunderstorm as an existing natural phenomenon, but at the same time realize that the characteristics of the lightning which it produces must be determined before a completely satisfactory solution of the protection problem can be attained.

We can accept as a fact, requiring no detailed proof, that condition in which potentials, or voltages, are built up between and within clouds and between cloud and earth, resulting in the passage of electricity. This latter we call lightning. And there is something in the process by which this discharge travels between cloud and ground which aids us in understanding lightning's habits and characteristics, and the roles that are played by cloud and earth respectively in determining what happens.

Since direct proof of all the conditions to be described here is not available, some of the story must be accepted on faith. Yet sufficient facts have been discov-

ered to make the picture seem reasonable. The future may clear up the rest.

We have discussed previously the conditions which exist prior to a stroke of lightning, with reference to the release of *bound* charges. As you stand, for example, in an open outdoor space and look upward to the summer sky, you may assume that both the cloud overhead and the earth beneath your feet possess substantially equal quantities of positive and negative electrical charges, so that neither of them possesses an excess of either the positive or the negative, although, strictly speaking, the earth is normally negative.

Then the mechanism of the lightning storm begins to go into action overhead and the electrical charges in the cloud separate. The positive charges move to the upper regions, while the negative charges become concentrated in the lower region nearest the earth. Actually, as the reader will readily perceive, the picture is not quite this simple, for there are other charged clouds near by, and even within the one cloud there may well be many regions of charges of different sign. For our purpose, however, the simple cloud with a positive upper region and negative lower region will do nicely.

The alignment described above is not altogether arbitrary. There *may* be strokes to ground from positive-polarity clouds, yet we know that strokes to transmission lines and tall, grounded structures are from negatively charged cloud regions in at least 95 per cent

of the recorded strokes. In fact, the percentage is probably higher, as will be seen later from our studies in New York City.

To return to the cloud overhead, as it builds up its negative charges in the lower region, positive charges, as discussed in a previous chapter, are being separated from the negative in the ground beneath your feet. The negative earth charges move away to more remote points. Other things being equal, the negative concentration in the cloud will be greatest at the point nearest the earth. (Although we began this picture with the reader imagining himself as standing directly beneath the cloud, it will serve the interests of both safety and clarity if he will now remove himself to one side and imagine instead that there are trees or other objects in his place.) Concentrations of positive charges in the ground will now be in the tops of trees or other objects capable of conducting electricity. This can be true even though the conductivity is poor, as with trees, since the preparation time before a stroke is often a matter of seconds or even minutes. This is now the *prestroke condition*, and it should be apparent that the electrical stress on a high object, so located beneath the cloud, may become great enough through such a concentration of charges to cause a discharge into the air of the type known as St. Elmo's fire.

In any case, the concentrations above and below continue to increase, feeding and controlling each other,

until a stroke takes place. *A single discharge?* Not necessarily. It has been known for many years that such a stroke is often actually multiple in character, there being a succession of discharges in the same path. W. N. Jennings, who has taken many interesting lightning photographs, remarked many years ago that he first realized the multiple character of the lightning stroke when he saw, during a lightning flash, the image of a flying bat in successive positions as it was illuminated by the successive discharges of the stroke.

As we realized that such successive discharges do occur, it became necessary for us in our work to distinguish between them, as their mechanism might well be different. Before continuing with our present dissection of the stroke, it is well to make the point that in nature, as in the laboratory, the shape or configuration of the electrodes (cloud and ground-objects in this case) may have much to do with what happens. There are two general sets of conditions to be considered. The first and most common is that in which the earth-electrode may be regarded as a plane, with the projections and bumps on its surface being relatively so small as to have no important influence of their own on the cloud. The second is that in which a tall building or other structure may represent an appreciable part of the distance between earth and cloud.

In the first instance, it is known from the experience of Schonland and his associates in South Africa that

when the electrical stress in the cloud becomes high enough to break down the resistance of the air immediately beneath it, a *streamer* forms and moves toward the earth at a speed of approximately 150 feet per microsecond for a distance of approximately 50 feet. This streamer then hesitates, stopping for about 100 microseconds, after which it resumes its headlong travel toward the ground. Again it travels a similar distance, hesitates, and once more moves toward the earth. This second section, or extension of the original streamer, is quite bright optically while it is traversing or breaking down the next step, but the original streamer to the cloud is difficult to photograph because of its low intensity. This connecting streamer feeds the onward moving tip, or front, of the whole streamer, and is of course continually becoming longer as it travels. A total time as great as a hundredth of a second, and as many as 40 or more steps, may be required to traverse the distance between cloud and ground, and between the cloud and the ground this hesitating, or "stepped leader," as it has been called, establishes an electrically conducting path. Why does it not follow a straight line —the shortest distance? Apparently the path chosen by the leader for most of its travel is determined by local conditions, since the conditions which are responsible for the formation of the stroke are continually changing. It simply selects the easiest path, and one that is probably determined by local ionizations existing at the

time, changing its direction many times in the course of its travel. If the stroke is to have a branch, it will usually result from the stepped leader dividing and establishing two paths, which look equally inviting to the downcoming leader.

As shown by Schonland's photographs, when the stepped leader completes its path to ground, something occurs which will seem strange to those who have always thought of lightning as striking downward. The earth strikes back, and a discharge moves upward from the ground through the channel prepared by the stepped leader. This discharge, moving with a speed of from a tenth to a half of that of light, is what the casual observer first sees. There are subsequent discharges—downward and upward—much like the initial discharge, except that the stepped leader has been replaced by a "continuous leader," having a velocity of from 3 to 300 feet per microsecond. Only rarely are streamers found on these subsequent discharges, although they have been recorded during field work.

Taking up now the second set of conditions, in which a sufficiently tall structure is involved, our work in New York City (in which we studied lightning striking the Empire State Building, 1250 feet high) disclosed stepped leaders which began, not at the cloud, but at the building, and proceeded upward through a series of steps. In this kind of warfare which is waged between cloud and earth, the burden of beginning the offensive

seems to be definitely on the side of the troops which are first ready, and in the case of the Empire State Building, the "positive" battalions are concentrated in a spearhead which is relatively sharp and extends almost a quarter of a mile into the air, instead of being distributed on a flat surface. In the case of the discharge from this building, the average length of the step was 25 feet, and the average time-interval of hesitation between steps was 30 millionths of a second. No return stroke, following the upward stepped leader, was ever found, but instead the current flow following the channel of the upward stepped leader would continue for several tenths of a second. We have called this a continuing discharge. Then succeeding discharges, having leaders of the continuous type beginning at the cloud and terminating at the building to be followed immediately by the upward-moving return stroke, occurred as under the first set of conditions described, and having about the same velocities. In this second picture of lightning, then, as it occurs in relation to tall structures, we find an *upward* stepped leader with a continuing discharge, with the remainder of the phenomenon being substantially the same as with the *downward* initial leader stroke to a plane or flat surface, as described by Schonland.

It must not be inferred that all of the strokes to the building have the initial upward stepped leader. Approximately one-quarter of the strokes to the building

began with the initial downward stepped leader like those observed by Schonland.

Taking one more look, just for the record, at what takes place during an average stroke of lightning, we find a downward leader, whether stepped or continuous, distributing negative charges from the cloud along its path, the effect on the positive charges in the ground being to draw them in to a point which is to be "struck." As these rapidly moving negative charges come closer and closer to the earth, the positive charges on the ground become more and more concentrated, until when the leader is within a few hundred feet or so of the ground, streamers from the earth may form to a length of 100 feet or more.

Included in this book is a photograph which will assist the reader in visualizing what happened in such a case—when lightning struck a beach in New Jersey about 100 feet from the camera. Three streamers can be seen extending upward from the ground, that on the right being forked upward. These streamers evidently formed while the leader was still some distance away. The center streamer was longer than the others, and when the leader made contact with it, the positive charges waiting in the earth underneath rushed up the channel, and the other ground streamers immediately disappeared. Such phenomena cannot be seen with the naked eye, because the return stroke from the ground is so brilliant that the streamers are lost. It is a rare occa-

sion when a camera is set up thus, to obtain a picture of the ground end of a stroke, and obtain a picture so satisfactory for study.

To go back once more to an important but admittedly difficult subject, which is badly in need of interesting illustration, let the reader, referring to the photograph just discussed, imagine that the center streamer is replaced by a conducting rod or mast. Then let him imagine that a cathode-ray oscillograph is connected to the rod in such a manner that it will indicate the waveform of the current changes that are taking place—and how fast. It seems reasonable to suppose that while the downcoming leader stroke is traversing the last 200 or 300 feet, the rapidly accumulating positive charges in the rod will be recorded as the "front" of the wave. As the leader rapidly approaches, in a period of time of from two to ten microseconds, the current in the rod will rise to a maximum, at which point downward leader and upward streamer meet. The "tail" of the recorded wave will then result from the flow of charges skyward from the earth, up the rod and into the channel prepared by the downward leader. The authors cannot resist this final attempt to show just what that interesting-appearing wave, photographed on film in the oscillograph, really represents in terms of a stroke of lightning. An understanding of the lightning wave, when coupled with a photograph of the same stroke, turns out to be exceedingly helpful in understanding

our effort to explain some of the mysteries of lightning.

Although the channel established by lightning between earth and cloud is conducting (as is a transmission line, but to a lesser degree), there seems to be no evidence of the flow of traveling waves up and down the stroke, as happens in the case of a transmission line. Furthermore, the availability of the charges in the earth is great, compared to the availability of charges in the cloud, on account of the discontinuous character of the cloud, which is the reason why there is no return stroke when the upward initial stepped leader reaches the cloud. On the other hand, when the downward leader makes contact with the earth, whether stepped or continuous, there is a return stroke, which means that the high currents associated with direct strokes come from the earth and not from the cloud. Thus, irrelevant as it may be to the party concerned, an individual who unfortunately gets in the way of a lightning stroke has probably been "struck up" from the ground, and not "struck down" from the sky.

But, if most of the high current of the lightning stroke is traceable to the ground, the cloud seems to have the honor of controlling the mechanism. Of course the cloud does the work of setting the stage, the earth reacting to the accumulation of cloud charges by setting aside charges of opposite polarity. Once the path to the ground has been established, the business of the

subsequent discharges goes on independently of the means by which the path was originally established. Cloud-to-cloud continuing discharges have been found, and also continuing discharges to the earth, both where the earth terminal is of high resistance and of low resistance. All of this would seem to indicate further that it is the character of the cloud which determines whether a stroke will be continuing. The resistance of the earth at the point struck will probably have something to do with the magnitude of the currents in return strokes as well as having some effect in determining the length of the tail of the wave. It also seems likely that strokes to extensively grounded systems covering considerable areas will reach higher crest currents with shorter times of discharge, all other factors being equal.

In some places, where soil conditions are right, nature has left a record of the passage of lightning currents in the form of a tree-like formation of fused sand called a fulgurite. We have attempted to produce these in the laboratory with the high-current short-time discharge, and succeeded only in blowing the sand out of the test container. However, tests made with low values of current, lasting several seconds, produced a fulgurite such as is illustrated. This work leads us to conclude that the presence of a fulgurite indicates a low-current continuing type of lightning discharge. It is likely that high values of current were not present, as this would

probably have blown the fused sand away. These fulgurites sometimes attain considerable dimensions, being several feet in length and inches in diameter.

It is pertinent to note that in the studies where we measured oscillographically the current to the Empire State Building, all of the lightning strokes began as from a negative cloud. At the end of the discharge period, three of the discharges changed to positive polarity, which we have taken to mean that new portions of the cloud were tapped where positive charges were available.

Thus we arrive at a point where we can sum up the picture of the stroke of lightning as consisting of not the traditional one, but many discharges in the same path, all, so far as is known, initiated from the cloud except in the case of the tall structure. The bright discharge which we customarily see comes from the ground and propagates to the cloud. It is now quite certain that once the conducting path between cloud and ground is established, current in varying magnitudes flows until the end of the stroke. In other words, the multiple or successive discharges appear to be superimposed on a more or less continuous current flow.

13. SKYSCRAPER FIREWORKS

THE difficulties experienced in devising the measuring devices for lightning study constituted a considerable problem in themselves; using these devices was another, for we obviously could not know where lightning was going to strike. Even the lightning bolt itself did not know when it started its journey from the cloud. In effect, we had with considerable pains built ourselves fine tools. When it came time to hitch our wagon to the lightning star and put our tools to work, we found that we were chasing something that was pretty elusive. Under such circumstances it is only natural that investigators began to resort to photography in studying lightning, for a camera need only be ready and in the storm vicinity to obtain its record, other things

being equal. Several varieties of camera were used.

In a day when photography has become universally popular, a brief mention of the various lightning cameras, their method of operation, and location may not be amiss. In 1900, long before the cathode-ray oscillograph was available in fact, Sir Charles Boys in London developed a special form of camera that was destined to become a highly important factor in unveiling some of the mysteries of lightning. Sir Charles himself did not enjoy much success with his camera, partly because in England there was not much lightning to photograph. However, Dr. Schonland and his associates in South Africa were successful in obtaining many valuable photographs, and these were reported to the Royal Society in 1934 and succeeding years.

An ordinary camera held still is of no use in analyzing a lightning stroke, because the image it obtains, while its shutter is open, is similar to that seen by the naked eye. It fails to indicate how long a discharge may have lasted, whether more than one discharge occurred, or whether the stroke was initiated in the cloud or on the ground. In other words, the still-camera photograph of lightning makes no record of the passage of time. The Boys camera, employing a rapidly moving lens or film, and with its shutter open during the entire time the stroke is taking place, supplies the time dimension. In the case of a continuing discharge, lasting many microseconds, the photograph will show a blur of light

the width of which indicates the total time elapsing during the stroke. In the case of several separate discharges, which may appear as one to the eye despite their individual character, the moving film or lens of the Boys camera succeeds in making the separation apparent.

If the lens or film is moved with sufficient rapidity, it is often possible to determine the characteristics of the leader, whether stepped or continuous, and also to determine the propagation velocity of the return stroke. To do this usually requires an equivalent film velocity of about a mile a minute. Such fast Boys cameras give the details of the individual discharges, while slow moving cameras are necessary to photograph the stroke during its whole duration, which may be of the order of a second or more. The Boys camera will tell the direction of propagation as well as the velocity, and it may divulge other secrets of the lightning discharge as well.

It has already been explained that Schonland found the stepped leader mechanism by which the initial path was formed between the cloud and the earth. This was frequently followed by a succession of discharges which were initiated by continuous leaders. Each of these leaders, whether initial stepped leaders or continuous leaders, was followed by a return stroke from the ground to the cloud. All of this and more Schonland found out from the use of a Boys camera such as we have described. In the study of lightning to the Empire

State Building the maximum time that any stroke lasted was 1.5 seconds. During this time the path of the stroke probably could not be blown distances much in excess of 100 feet. This means that the successive current peaks or discharges would all have much the same path, and changes in path could be determined from measurements made on the photographic film.

The important use of the Boys camera, running at high speed, was to determine propagation characteristics, including leaders and return strokes.

The first leader strokes photographed in the United States were obtained by W. L. Lloyd and W. A. McMorris with such a camera as that described above. The camera used was made in London for Sir Charles Boys and loaned to us by A. L. Loomis of Tuxedo Park, N. Y. The film operated at a speed of 145 feet per second, or roughly 100 miles an hour. Because a storm over the Empire State Building was usually rather brief, we designed another camera in 1936 for film speeds up to 344 feet per second. We found, with experience, that we were losing much data because of the decrease in exposure time of weak portions of a stroke (continuing illumination would seriously fog the film) and we eventually came down to a film velocity of 124 feet per second, with a short focal length of 1.38 inches.

A wide film is used in this camera, so arranged that successive exposures are possible. A variety of films were tried, but the so-called super-sensitive panchro-

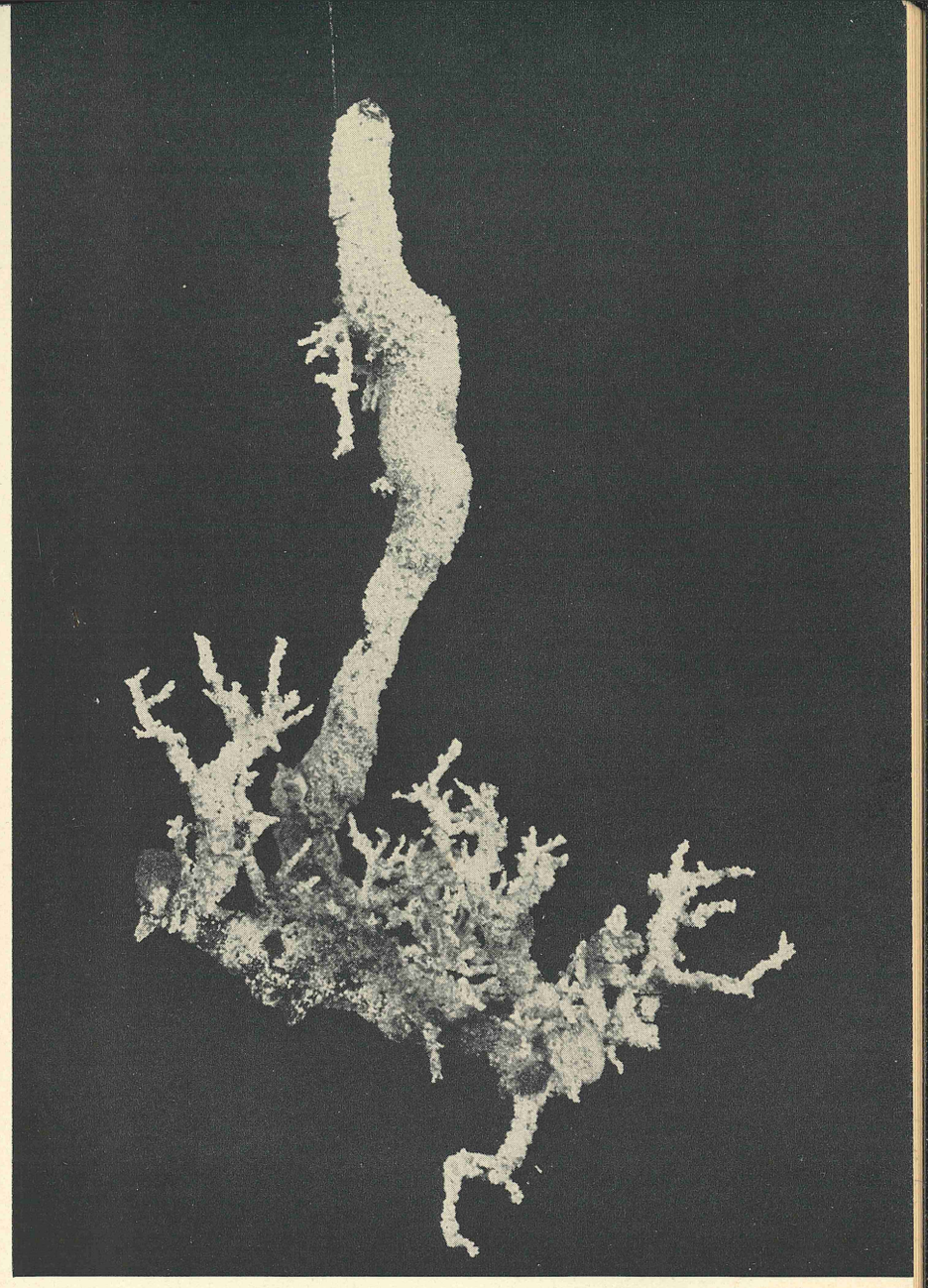
matic proved to be very satisfactory. For the purposes of study the image is greatly enlarged, and by this method we obtain most of the data on continuous and stepped leaders, as well as the rate at which the leader and return stroke propagate. At the film speed on which we standardized, one-thirty-second of an inch on the film is equal to approximately 20 microseconds. Another way of expressing this might be to say that in a picture an inch wide we are able to show the action which takes place in 640 millionths of a second. By suitably enlarging the image it is possible to determine changes taking place in ten microseconds, as indicated by changes in the photographic density.

Another type of camera we have used, to determine the sequence of multiple-stroke discharges, employed an eight-by-ten-inch film-holder with two matched lenses having a focal length of 3.07 inches. These lenses were mounted in front, one centering on the center of the film in the conventional manner, and the other revolving at a radius of two and seven-eighths inches around the center lens as an axis. In the first such camera built, the center lens also revolved on its own axis; in later cameras we made the center lens stationary. At first we operated this camera with the moving lens completing one revolution per second, only to find that some continuing strokes persisted for more than a second. Now we use two such cameras, one at one-half revolution per second, and the other at two revolutions

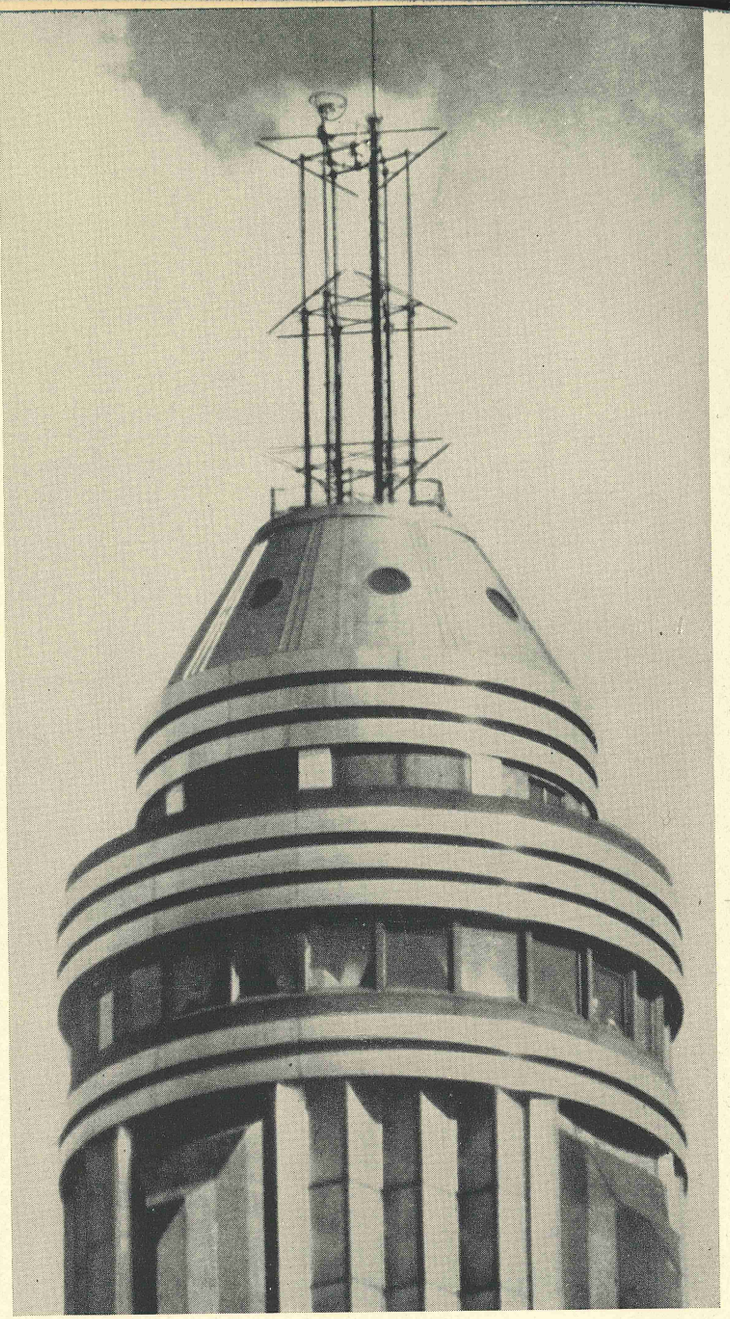
per second. Since the center photographs with each camera are taken with matched lenses, they can be put together to give a stereoscopic picture. The two cameras in action are on the same level, and separated by several inches.

Having two slow-speed cameras has proved very helpful in the analysis of results. The slower of the two gives better over-all data, while the faster gives better resolution of the individual discharges. Furthermore, having two cameras of this type makes it quite certain that for most strokes the image will be in a good position for study on one or the other.

Having described our principal photographic tools, we are now in a position to describe how they were used. Previously we mentioned the difficulty which faced us in catching up with lightning bolts in order that we might use our fine tools. The decision to employ photography to obtain certain results simplified this phase of the problem somewhat, and the next question was to find a reliable studio, one which lightning might reasonably visit a number of times during the year. Curiously enough, we found our studio right on Fifth Avenue, in New York, in a quarter popular with portrait photographers having a clientele somewhat different from ours. Our selection was the Empire State Building, and we established our reception room just as high up as possible, right at the mooring mast. Another tenant was there ahead of us even then, the Na-



Fulgurite made in High-Voltage Laboratory at Pittsfield by F. W. Peek, resulting from flow of a few amperes at high voltage through sand. Current was maintained until sand melted to form fulgurite. Low-current discharges persisting for about one second cause formation of similar fulgurites as the result of natural lightning discharges.



The antenna system atop the Empire State Building, completed in this form in July, 1936. Oscillographs connected to highest antenna.

tional Broadcasting Company, but through their courtesy we were allowed to move in.

We had become convinced that it would be desirable to obtain simultaneously Boys camera photographs and oscillograms of the same stroke. The photographs would yield information concerning the direction and speed of propagation, and the oscillograms would measure the lightning current. When we put the two together, we would have as complete a story on each lightning stroke as it was then possible to obtain. The Empire State Building seemed ideally suited for such an investigation, and we had already installed there lightning stroke recorders to measure the current flowing through the NBC television antennas. The cameras could be located a fixed and known distance away from the building. The means had to be found to introduce a suitable shunt, or by-pass, between the television antenna and the frame of the building, so that, without interfering with the television experiments, it would be possible to measure lightning wave-shapes using a cathode-ray oscillograph. The National Broadcasting Company gave us all the assistance that could have been desired, and accordingly such equipment was installed and operated for the first time in 1935. We did not succeed in securing satisfactory oscillographic records until 1937, but in that year the crater lamp oscillograph, which had been installed the year before, produced many good records. In 1938 we obtained the first high-

speed cathode-ray oscillograph records of the current in a direct stroke to be obtained in the United States.

One of our objectives in the designing of the cathode-ray oscillograph equipment was that it be capable not only of recording the wave-shape of the first stroke in a series of multiple discharges, but that it get the wave-shapes of all successive discharges occurring within one second. Several schemes were tried, but only the one used in 1938 will be mentioned here.

The Empire State Building is a steel frame structure surmounted by a tower, the top of which is 1250 feet above the street. The tower top is of metal, and the television antenna system extends above it. The oscillographic equipment was located just below the roof, about on a level with the port-holes which appear in the picture facing page 141. The antenna rod to which our equipment was connected terminated at a point 38 feet above the top of the building, and it was here that we prepared to entertain lightning.

The most severe strokes could not be measured with the oscillograph because the insulator above the shunt would flashover, short-circuiting our equipment. Because we wanted to measure both high and low currents with the same setup, a special shunt was built using Thyrite, which has the property of low resistance at high currents and high resistance at low currents. This arrangement was very useful. With fair accuracy we could record current of the order of 5000 amperes

or of 100,000 amperes without exceeding the measuring range of the oscillograph.

The oscillograph was of the hot-cathode type, using a sealed tube and outside photography. Since no attendant would be present during a storm, it was necessary that operation be as automatic as possible, and the scheme of that operation was as follows:

When lightning strikes the antenna overhead, current begins to rise rapidly through the shunt, just as it was observed to do in the case of the traveling wave on the transmission line. The electronic beam of the oscillograph which has previously been kept off the fluorescent screen, is swept across the screen on the bottom of the tube at a rate such that the full distance from one side to the other represents 100 microseconds. A curious factor enters here. About one microsecond is needed to get the cathode beam in place, and lightning, which is knocking on our studio door at the top of the antenna, must be detoured until all is ready. This is done by passing the impulse through an air-core delay cable of such length that when it finally arrives at the cathode-ray tube the beam is ready to record. Something similar happens at the race track, to take a very rough comparison, when the official starter imposes a mechanical barrier before the prancing horses until all are in line and the race can begin.

The oscillograph, however remote it may be from the lives of most readers, deserves a certain amount of

applause for the finesse with which it performs an exceedingly delicate task. After a recording time of 100 microseconds has passed, the device becomes inoperative for a brief period, after which it is ready to repeat the cycle. A large drum carries film and rotates at a film velocity of about nine feet per second. Any succession of records appearing on the fluorescent screen are photographed in their proper sequence on the revolving film, and the record shows the wave-shape and the time intervals between succeeding lightning discharges. In 1938, this oscillograph obtained the first known records to be made of successive discharges of continuing lightning strokes, recording the entire wave-shape of as many as twelve discharges in a total time of 0.28 second. The time at which each stroke was obtained was highly important, since the records had to be correlated with the Boys camera photographs later. Among other things, the oscillograph was capable of changing its film after each record.

Before leaving the subject of oscillographs, it should be noted that the second oscillograph, of the slow-speed crater lamp type, was installed for the purpose of recording continuously the changes in current over at least an entire second, since our photographic records led us to believe that current was flowing over much longer periods of time than was originally expected. This oscillograph was adjusted to record currents as small as 20 amperes.

Although lightning sat for its portrait at the Empire State Building, the picture had to be made elsewhere. Except for the first year of the investigation, the photographic equipment has been located at 500 Fifth Avenue, a building situated at the intersection of Fifth Avenue and Forty-second Street, eight city blocks away. This building is ideally located for the purpose since not only is an excellent view obtained of the Empire State tower, but the cameras are able to photograph a large number of strokes to lower Manhattan. During the second and third years of the investigation, the only office space that could be obtained was that made available through the courtesy of the Fletcher and Ellis advertising agency. Since, from our preceding description of the cameras used, the reader must be somewhat aware of the space and the facilities required, he will probably wonder at the generosity and tolerance of human beings in general, and the advertising men in particular, in making room for us. As a matter of fact, the space allotted had to be in use every day, but since we worked only at night we overcame the obvious difficulties by building a pipe frame over the desk in the room and locating the equipment on it. When the operator arrived to go into action, he would pull the desk away and operate a winch to lower the cameras into position in front of the window. More recently, we have been able to obtain quarters of our own in this building.

More than cameras was necessary to do the job, however. To keep a satisfactory record of the times of exposure of the various cameras, a device used by telephone companies when timing toll messages was employed. This is known as a calculograph, and it has the happy faculty of being able to record the time at which the shutter of any camera is opened, and the elapsed time it stays in that condition, even though other timing operations are begun and stopped in the meantime. Each camera had a printed ticket on which essential data, such as stop opening, kind of film, and other facts were recorded. The time of day and the elapsed time, as indicated by the calculograph, were stamped on each ticket.

An ediphone was also provided for the recording of incidental facts, because in practice the operator is too busy to write down his observations, and, moreover, is working in the dark. He wears a lapel microphone, making it necessary only to change ediphone records, and freeing his hands for other tasks.

Based upon the sound of corona, and the discharges from one's fingers when standing on the small balcony near the top of the Empire State Building when storms are several miles away, it was thought that a stroke to the building could be anticipated if streamers from the building could be seen during storms at night. A careful watch was kept, and during 1937 we added to the equipment at 500 Fifth Avenue a 35-power telescope

for this purpose, but as we later found out, the corona streamer built up into a stroke so fast that the eye could detect no time interval between the two.

In 1938 we began to use a third type of camera. For want of a better name it has been called the multiple-aperture camera, and it was designed primarily so that we might take a closer look at what we were photographing. Every amateur photographer knows how a different stop opening can change a picture, and wishes afterward that he "had given it more (or less) time." We did not want to miss anything while we were about it, and we especially desired to measure the density, or brightness, of the lightning stroke in its various phases, since such a record, if properly calibrated, could be made to speak to us in terms of amperes. By making a number of photographs of the same flash, under various timing conditions, we could always be sure of being able to measure the intensity of practically any part of the stroke on some one of the different exposures made. The camera used makes possible the measurement of the density of the photographic record by employing four matched lenses, each with a different stop opening, or stop plus a neutral filter, so that a latitude of about a million to one could be obtained when photographing the same stroke. Using a device called the microphotometer, especially built for this purpose, we can record measurements of density from point to point on the film. The focal length of the lenses permits much

greater detail than has been possible heretofore in this study. Since each exposure requires the entire width of the film, it has been necessary to incorporate a method of winding an unexposed section of film into place in a few seconds.

This camera has already given results of great interest, and it is hoped that future photographic records will be obtained which can be translated into amperes so that the current-time relations of the stroke may be had with reasonable accuracy.

In the following chapters we will attempt to set forth some of the interesting and valuable information we have obtained in regard to lightning storms over New York City and elsewhere, but it would be highly unjust to close this one without due regard to the human elements involved in the investigation. Overzealous, perhaps, in describing the admirable oscillographic and photographic equipment, with its many automatic features, we have proceeded somewhat as though everything clicked into place and began to function as soon as lightning showed over the horizon. Of course this is not so.

During the first two "seasons" at the Empire State Building, the young engineers who were in charge were unmarried. During every summer since that time we have had married men on the job. There is no connection, let us hasten to add, between that circumstance and the activity itself, although there are a number of

peculiarities in the routine of the five-month annual tour of duty in Manhattan which are certainly characteristic of no other form of employment that comes to mind. The man who qualifies must be part electrical engineer, photographer, and night watchman. Somewhere along the line in that strange mixture of talents a wife is pretty likely to be useful, if only to take her turn by the telephone while her husband goes to the barber's.

Contrary to normal expectation, the Weather Bureau in New York does not play a large part in this routine. Most of the thunderstorms that sweep across New York originate in the regions west of the Hudson River, and reports from New Jersey turn out to be most helpful. Storm tips usually originate in the organization of the Public Service Electric and Gas Company of New Jersey, or with the Weather Bureau at the Newark airport, and one or both of these will telephone the hotel of the lightning investigator in New York. The latter never strays very far away, especially when the sky is cloudy. Probably he has selected a hotel room which faces toward New Jersey, just to be on the safe side, and one which is relatively high up from the street level. One man was so well trained that a flash on the horizon would find him on his way, even before a call from the power company. Nearly all of the men, during the months from May through Sep-

tember, when they are on call, acquire a "feel" for a coming storm.

As far as the photography is concerned, night work is the rule, although oscillograms can be made just as well during daytime periods. The engineer, once aroused by the storm warning, must hurriedly leap into his clothes, find a taxicab, and hasten to the Empire State Building. The hour may well be, and often is, after midnight, which means that a night elevator man must be found to make the trip to the one-hundred and second floor. Then there are two flights of iron stairs to be covered after that. Once on location, it is only necessary to close the proper switches, wait for the oscillographic apparatus to heat up, and give the devices a quick checking over. Then the order of the night is: down the iron stairs, down in the elevator, and into a cab for the journey to 500 Fifth Avenue, where the same kind of elevator service must be called upon. The cameras are usually located 50 or 60 stories up, and a couple of minutes are required to place them in operation. All this time the storm is on its way, or so the investigator hopes; for down in the street it is usually impossible to follow developments. In all too many instances the whole thing turns out to be a false alarm, and there is nothing to do but turn off the equipment, make necessary notes, and go home again. There may be later calls on the same night, which must be answered with a similar headlong trip.

The success of a lightning hunter's season, cast in the mold that has been indicated above, is a matter over which he can have little control. During the first three years, the Empire State Building was known to have been struck 68 times, and in one year 19 oscillographic and photographic records were obtained simultaneously. On the other hand, by mid-August of 1939, after three and a half months of application to the job, not a single stroke had been photographed because of the almost complete lack of thunderstorms. Such a deficiency may well be made up in a single night, however. If Franklin could have spent one such night at the Manhattan headquarters of the modern lightning hunter, he would have had to remake the whole front page of Poor Richard's Almanac.

14. FREEZING LIGHTNING ON FILM

BEFORE we approach some of the results obtained with the equipment described in the previous chapter, there is still another lightning-observation post to be covered, a veritable crow's nest in the Berkshires, right at our lightning headquarters. We realized early that when we made use of a tall structure like the Empire State Building, the structure acted as a great needle point, and naturally might exert a marked influence on the character of the discharge. The Empire State Building was selected somewhat because of its limitations, because it offered us a theater of operations in which lightning was sure to make many appearances. But we needed also to study the random bolts that roamed the heavens in open country, striking relatively level sur-

faces and other areas whose reactions would not be governed by the circumstances prevailing in Manhattan. It was evident that once we attempted this task, however, we would thereby increase the difficulties, for we would be attempting to photograph lightning which might strike on any side. Our new proscenium arch had to have a dimension of 360 degrees, and our equipment would have to have eyes in the back and sides of its head.

The laboratory which we erected in 1934 on the roof of one of the largest factory buildings in Pittsfield, Massachusetts, was a unique structure. Built almost entirely of steel and glass, it has three main divisions, or layers, from top to bottom, and is circular in shape. The observatory proper is in the top section. Completely surrounded by plate-glass windows, it supplies to the observer an unobstructed view of the entire countryside. It is the kind of a room which one who was habitually afraid of lightning might find himself inhabiting in his worst nightmares, for if there is lightning anywhere on the horizon, we are sure to get it. Aluminum paint covers the outside of the building to reflect light and heat, while the interior is painted in a flat black color to prevent reflections. Within the circular room is a platform surrounded by black curtains which can be lowered at will to form a light-tight enclosure seven feet across. In this dark room is placed a periscope eyepiece.

Much as the commander of a submarine is able to watch the movements of ships on the surface of the sea through his periscope, our engineers are able to watch for lightning here when there are storms abroad. But this periscope does not have to be swung around to command a full view. It operates through the use of a crystal sphere eight inches in diameter, located at the peak of the observatory. The sphere's brilliant silvered surface reflects lightning flashes from every direction, and sends the images down through a dark-walled tube to a mirror which is set at an angle of 45 degrees. By looking through the periscope it is possible to see the visible image of any lightning flash anywhere on the horizon. The periscope is used for visual observation only.

Below the observatory proper is located the multiple-lens camera, with its twelve lenses set like eyes in a circle. To prevent rain from driving against the lenses and thereby spoiling the clarity of the pictures, a special air ring was mounted around the camera, and through it compressed air is forced when we are in action. The surrounding curtain of air is strong enough to serve our purposes in all but the most severe storms, acting as a sort of invisible, transparent wall between rain and camera.

The camera itself, built especially for the Pittsfield job, uses a film revolving at one revolution per second, and is provided with 12 similar lenses, the shutters of

which can be opened or closed at will. The camera is mounted in a fixed position with each of the lenses covering one-twelfth of the horizon.

The staff of the Pittsfield Observatory has had to operate in much the same headlong manner as that in New York, on a schedule laid out by the elements without warning, and with a time clock punched by the ominous crack of thunder. Obviously there could be no direct oscillographic recording possible here. The results which were obtained have been used to supplement those obtained in New York and to show what can be expected when tall structures are not involved. The observatory was protected by two lightning masts, and to our knowledge these have never been struck, although strokes have occurred within 1000 feet, which seemed uncomfortably close.

Speaking of thunder, it played an important role at the Pittsfield crow's nest. We had available daylight photographs of the terrain covered by each lens, and in some cases it was possible to locate the stroke which occurred at night and thus determine its distance away. We were without the convenient fixed distances which prevail in the New York setup between the camera and the point struck. In most cases, however, we have had to depend on the time interval between the lightning and the thunder, knowing that sound travels roughly 1100 feet per second. In many cases this method is unsatisfactory, not only on account of the

wind and other factors affecting sound velocity, but because it is often difficult to establish which thunder belongs with which lightning. As has been pointed out previously, the distance to the stroke being photographed is very essential if the photograph is to give us accurate data on the stroke. If light intensities are to be used, following the method described in the preceding chapter, not only the distance must be known, but the visibility is of great importance, as it affects the calibration directly.

For all of these reasons we have had to become somewhat familiar with thunder. We have spoken of lightning strokes consisting of a multiplicity of discharges through the same path. These discharges—sometimes as many as ten—appear to the eye as a single stroke, or in cases where the time interval between the discharges is sufficient, they present a flickering appearance to the eye. The sound of thunder from such discharges is likely to be of the so-called tearing or ripping variety, because of the separate sounds occurring from each discharge.

Not every lightning flash is accompanied by a clap of thunder, as is popularly supposed. There are, sometimes, lightning strokes which produce little or no thunder at all. Such flashes may appear just as bright as the noisy ones, but their destructive force is less. Thunder is the result of a steep pressure-wave caused by the sudden expansion of air created by a fast lightning dis-

charge. All flashes do not release energy with the same speed. Our studies have revealed that in some cases the electrical current is built up and released slowly, in one- or two-tenths of a second, as compared to millionths of a second in other discharges. This so-called slow lightning does not produce thunder as it is usually identified. To the human eye it appears the same, and during a general storm the fact that one hears no thunder in connection with a given stroke is often overlooked. Thus far the thunderless type of lightning has only been observed in connection with strokes to tall structures where upward initial leaders are present. If subsequent discharges occur, thunder will be heard from them, since they are the result of downward leaders and the current will build up with great rapidity.

Although it had been reported by the Superintendent of Buildings in Washington, D. C., that thunderless lightning struck the Washington Monument in 1885, apparently no one investigated the matter until we began our studies. Most thunder does not reach the ears as a single crack, because of the speed at which sound travels. One portion of a lightning discharge in the clouds may be six seconds away, whereas that portion of the stroke near the earth may be only one second away—in terms of sound, that is, not of lightning itself. The reflection of sound from clouds, hills, and buildings all tends to increase the echo effect, just as a pistol shot in a large empty building will echo and re-echo.

Considerable space in this account has been devoted to the camera equipment used in the study of lightning, partly because a knowledge of it will aid in understanding the results, and partly because some ingenious readers may want to take lightning photographs. It would not be too difficult to build some of this equipment for home use.

We have obtained a large amount of data during recent years, but will select here only a few records of lightning frozen on film to indicate the validity of the measurements and illustrate the basis for the picture we have painted of the lightning stroke. In the previous chapter we indicated the number of times that the Empire State Building was struck over a period of a few years. Slow-speed oscillograms were obtained in 1937 and 1938; high-speed cathode-ray oscillograms only in 1938; Boys camera photographs were obtained during every year in varying quantities.

Because what the human eye sees in a lightning stroke is found most nearly in the slow-speed camera pictures, we will look first at those. When the reader inspects these photographs, as found in this book, he must remember that the center image is what the eye sees, while the outer, or peripheral photograph, is the result of drawing the same image along a circular axis during the period of time in which the discharge takes place. We have already explained how and why this is done.

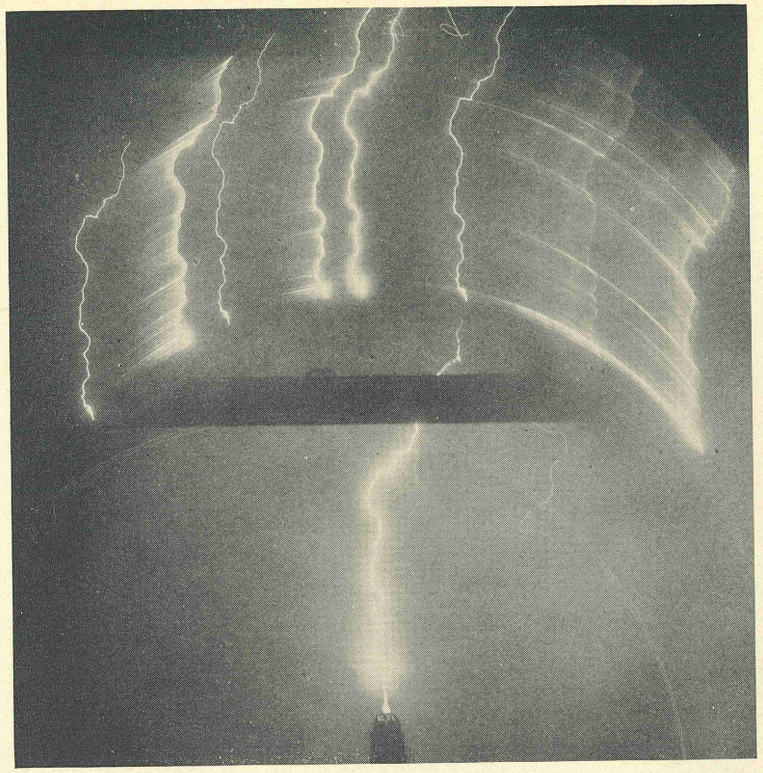
It will be recalled that a large percentage of the strokes to the Empire State Building are initiated by upward stepped leaders, since the building represents a great needle on the surface of the earth. These are best seen through the use of the high-speed Boys camera, but their presence can often be detected on the slow-speed records. In a typical photograph, for example, there may be seen a succession of early faint discharges, progressively extending themselves higher and higher up from the building. Once the stroke was established, current continued to flow more or less steadily for almost 0.3 second. The center picture alone, which is what the eye would see, does not disclose that information, but the circular streaks of light tell that story.

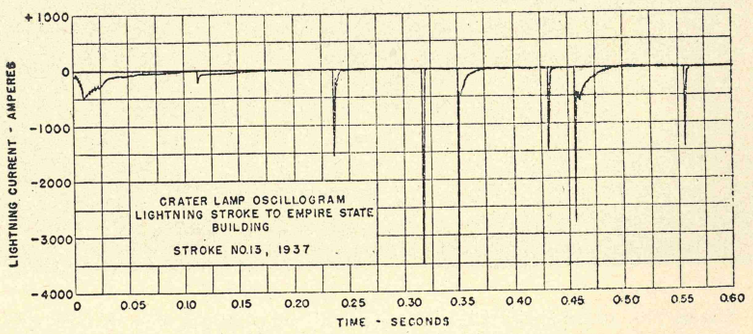
Typical of another variety of upward leader initiated stroke is No. 13, a photograph of which is reproduced. This stroke began, as revealed by the circular record, with a low-intensity long-continuing discharge, followed by six subsequent discharges. Yet to the human eye, as disclosed by the center picture, it would not look much different from the stroke just described in the last paragraph, which was a single discharge. The crater lamp oscillogram has also been reproduced for comparison. The engineer gets a thrill when oscillograms and photographs check closely. Our records indicate clearly that there is no predetermined order of discharge of various magnitudes, and since the ground

characteristics of the building itself do not change, obviously these differences must be due to differences in the charges of the clouds.

Of all the discharges measured oscillographically over quite a period of time, only three showed reversal of polarity. In each case the cloud was negative with respect to the building when the discharge began, but eventually the polarity, as recorded by our instruments, changed to positive. This always occurred at the end, however, and seems to bear out our contention given earlier that generally the base of the thundercloud is negative, with the positive cloud-charges in the upper or remote regions, which may be reached after the discharge has had time to tap more remote portions of the cloud.

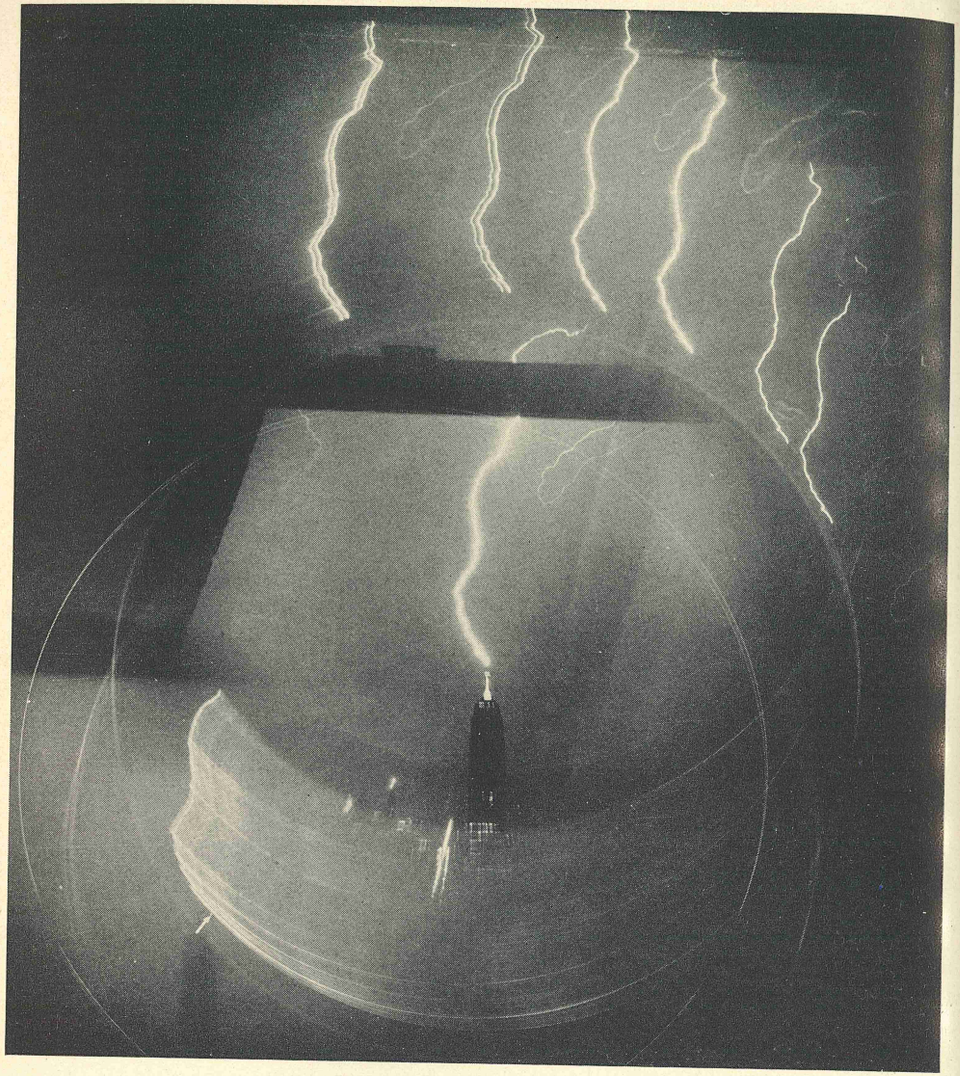
Of 17 lightning strokes to the building, which we photographed in 1936, 13 were definitely begun by upward stepped leaders. In 1937, out of 36 strokes to the building, 23 had upward stepped leaders. The remaining four strokes of the 1936 season could not be identified. All of those identified as having upward leaders were associated with a continuing stroke. Of the remaining 13 strokes in 1937, two had initial upward continuous leaders, two had initial downward continuous leaders, and nine remained without sufficient data to classify. Although all of the upward leaders initiated continuing strokes, and all continuing strokes for which leader-data were available had upward leaders, we are



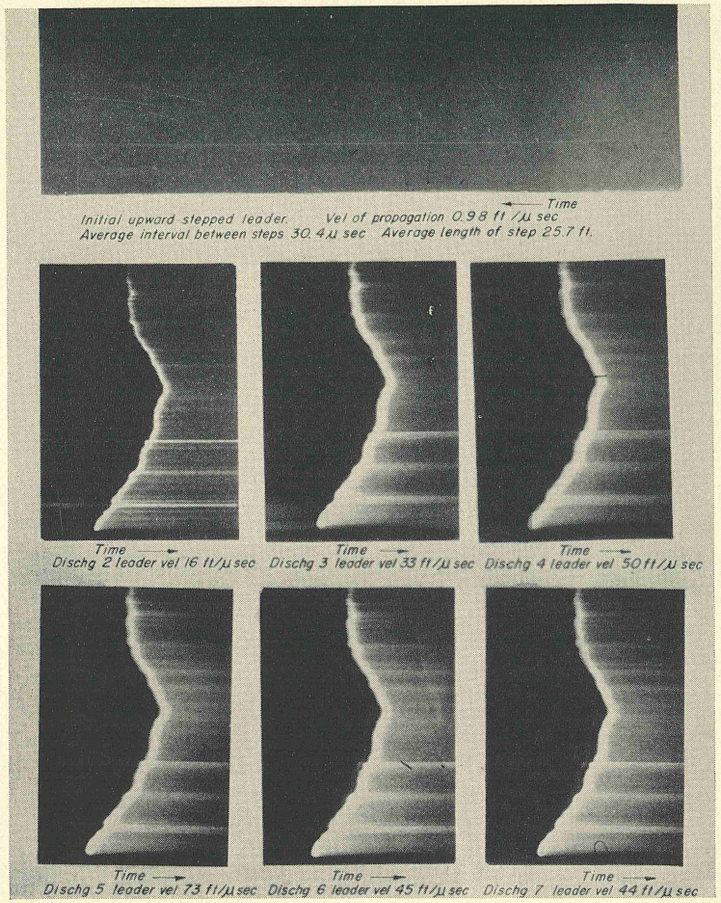


(*Top*) Still- and moving-lens photographs of stroke No. 13. Oscillogram of same stroke is shown. Notice close correlation between current magnitude and photographic density. Record taken in 1937.

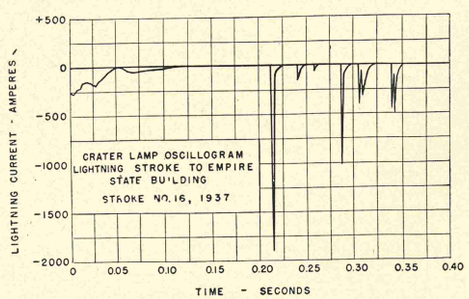
Replot of oscillogram. Note that time scale begins on left while time scale for photograph above begins on right.



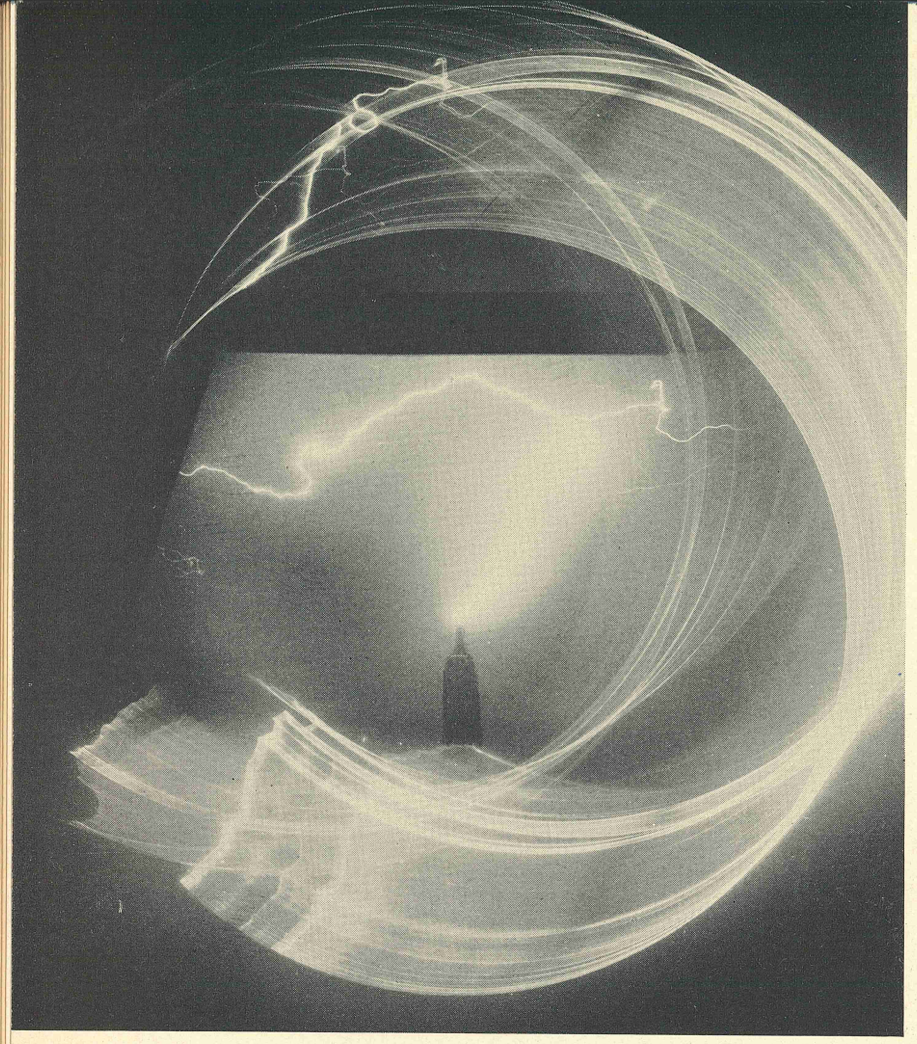
Stroke No. 16, taken in August, 1937. Still-lens photograph is in center. Rotating-lens record begins at lower left with an upward stepped leader followed by continuous current as long as illumination persists. This initial continuing discharge is followed by six further discharges, each of which has a downward continuous leader.


Time
Initial upward stepped leader. Vel of propagation 0.98 ft /μ sec
Average interval between steps 30.4 μ sec Average length of step 25.7 ft.
Time
Dischg 2 leader vel 16 ft/μ sec
Time
Dischg 3 leader vel 33 ft/μ sec
Time
Dischg 4 leader vel 50 ft/μ sec
Time
Dischg 5 leader vel 73 ft/μ sec
Time
Dischg 6 leader vel 45 ft/μ sec
Time
Dischg 7 leader vel 44 ft/μ sec

Multiple stroke to Empire State tower, consisting of a long-continuing low-current discharge preceded by initial upward stepped leader and followed by six non-continuing discharges all having downward continuous leaders. These are high-speed Boys camera photographs of stroke No. 16, taken August 11, 1937. Oscillogram of this stroke shown below.



Oscillogram of stroke No. 16, showing steady current-flow in beginning, followed by six current-peaks of widely different values. Oscillograph is delayed slightly compared to photograph of this stroke.



Long-continuing upward leader stroke showing upward branching. Part of left branch is cut off by window at beginning of rotating image. Period of streamer build-up is clearly shown at beginning of discharge. After this period is over, discharge becomes almost steady direct-current arc with heavy current-peak at end. Total time of discharge is 0.616 second. Charge in coulombs is 99, much above average in New York.

faced with the fact that some time in the future we will find downward stepped leaders to the building which initiate continuing strokes, or else it will have to be concluded that this situation is peculiar to this tall structure, since initially continuing strokes were found in Pittsfield having downward initial leaders.

An interesting photograph, on page 160, for which both camera records and oscillographic records are available, shows a multiple stroke consisting of a long-continuing low-current discharge, followed by six non-continuing discharges. The stroke, as photographed by the rotating lens, begins in the lower left corner, with an upward stepped leader, and the illumination gradually dies out. Later, it is followed by six successive discharges. The last two discharges are apparently made up of two separate discharges each, but the oscillograph recorded them as one discharge, and this was confirmed by the high-speed photograph taken at the same time. The latter film told us even more about this stroke. It showed the upward moving leader as a series of bright dots, 23 in all. Each dot represented a step in the leader's progress, and was connected to the tip of the tower by a streamer. This streamer moved upward at a speed of approximately 200 feet every millionth of a second, for each section. As each section approached the end of its travels, it would stop for about 30.4 microseconds, which made the average over-all speed of the leader 0.98 feet per microsecond. The average

length of the steps was 25.7 feet. Perhaps this detail, so important to the lightning engineer, will not be of great interest to the reader, but it cannot do otherwise than command his respect when he compares such a relative wealth of information with the image of the single fiery stroke appearing in the center of the photograph, and recalls that the *dossier* was obtained by a single human being working in the dark a half mile away. We present the picture here as ample evidence that you cannot always believe what you see with the naked eye.

There has been considerable controversy among meteorologists, both here and abroad, concerning the meaning of the direction taken by the branching-off of lightning discharges. There now seems to be little doubt but that the direction in which the lightning stroke is being propagated can be determined from the direction of the streamers, where they are visible. In every case of downward initial leader seen by us, the visible streamers were directed downward. Upward branching from the Empire State Building has been photographed several times, and seems to be the result of upward propagation of the initial stepped leader. It has been held by some investigators that branching was an indication of polarity, and that downward branching indicated a discharge from a positive cloud. However, both upward and downward initial leader strokes have been recorded which had negative polarity. Therefore, it seems certain that branching is deter-

mined by the direction of propagation, and the direction of propagation in turn by the shape of the electrodes. Tests in the laboratory with the artificial lightning generator bear out this conclusion.

An upward branching stroke is shown facing page 161. The moving-film record shows that the stroke began at the building and progressed upward, taking the path to the upper left. This path, estimated to be 10,000 feet long, was completed in 0.024 second. The feeder streamers continued to feed into the stroke, and another branch formed to the right, completed in 0.002 second. As illumination persisted in the main channel and branches, the right branch at length died out. Then a heavy discharge took place, preceded by a continuous leader, which re-established the right branch. The latter immediately died out. Just prior to the time of this discharge the oscillograph measured current at substantially zero, but it increased to about 3000 amperes, decreasing to zero in about 0.004 second.

Since the electrostatic field is along smooth curved lines, it is very evident that lightning and sparks, in general, do not follow the direction of the field. This is because the breakdown of air is not simultaneous over the length of the lightning's path, and the progressing streamer picks out the best path from instant to instant. The result is the crooked path so familiar to anyone who observes lightning. Since this is true, it is not difficult to understand why lightning does not always

strike the highest object. Where upward leaders determine the path, the stroke presumably will be from the highest point, as in the case of the Empire State Building, but with downward leaders the best path may not always be the shortest path, and the attractiveness of one path over another may change even during the progress of a multiple stroke.

Often one sees strokes branching, with both branches striking the ground, and expect that both occurred simultaneously. While we know this can happen, and have recent records to prove the case, yet very often your eye deceives you, because really the path changed between discharges. In one case four discharges could be seen. The first discharge struck a building that was 360 feet high, located 1200 feet west of the Empire State Building. Since this discharge was branched downward, we could assume in the light of present knowledge that it had a downward leader progressing from the cloud to the building, which was the first target. But the three following discharges, with the waywardness of lightning, left the first discharge at a point 655 feet above the Empire State Building. The first one branched downward approximately 550 feet above the Empire State tower, and the remaining discharges had no branches that could be determined. It may be that a streamer built up from the tower to change the course of the succeeding discharges. There is no evidence to support this, although it is what might

be expected. This stroke illustrates the area protected by the building—the discharges contacting either the building or hitting a point 1200 feet away. This is approximately a one-to-one cone of protection.

In the chapter on Laboratory Lightning we illustrated the rule of the cone of protection afforded by a tall structure. Out of a total of 46 strokes recorded to the Empire State Building at the time of this writing, only one has terminated within a cone having a base radius on the ground of 1200 feet, and that one terminated 16 feet down from the top of the antenna. This fact should reassure any timid tenants of buildings in the immediate vicinity of that structure. If they like, they can determine the cone for themselves with a minimum of figuring, and locate their place of residence or business in relation to it.

Our cameras occasionally pick up strokes which fall outside the stage of our immediate operations, and one such served as a rather exciting backdrop for the Empire State tower, and the brilliant lights of Fifth Avenue in the foreground. The picture might well have contemporary political interpretation, in a facetious sense, since it shows forked lightning striking Manhattan's financial district. The upper fork was about 4000 feet above ground, and there is a possibility that all five discharges reaching buildings on Wall Street are part of the same stroke. The upper portion is not clear, and without the moving-film record we cannot interpret

what happened. The observers were inclined to think that it was a case of changing path, of the type discussed in the preceding paragraph, although this is not necessarily true.

There has been some discussion among lightning hunters of the possibility of upward streamers occurring without having a stroke occur at that point. The photograph of lightning striking a New Jersey beach, mentioned previously, showed upward streamers in action, but the stroke took place at substantially the same point. In 1937 we photographed two such streamers from the Empire State Building which did not result in a stroke. One of these was about 300 feet long, and apparently took place at the time of a cloud to cloud discharge, when a branch downward came within 400 feet of the top of the tower. The upward streamer came within 130 feet of the downward branch, but evidently was not attractive enough to lure the stroke in its direction. Another such upward streamer, 85 feet long, was photographed extending from the Metropolitan Life Insurance Building, a structure 657 feet high and located 2100 feet from the Empire State Building.

Returning momentarily to thunder, our engineer operating the cameras during 1935 reported that on two occasions he saw strokes to the building but did not hear thunder, at least in the ordinary sense. He described the sound as what would be heard if a paper bag full of water were dropped for a short distance. In the light

of what we know now, we think that this "silent lightning" will result from an upward streamer of small magnitude, followed by a continuing discharge having no steep current peaks. Such a continuing stroke is really a direct-current arc, and might well give the appearance of a severe stroke of lightning without much, if any, thunder. In many cases during the 1936-37 seasons, the noise of our cameras was such that observations of thunder were often unsatisfactory. In view of the foregoing, we do not expect to view "silent lightning," except to tall, exposed structures, since upward leader strokes seldom occur under other circumstances. Downward leader strokes always involve fast rates of current rise, giving audible thunder, even though the maximum current need not be high. Once more, it is the *rate* of increase, as well as the amount, that must be considered.

Freak pictures are often sent to us for interpretation, and one of the strangest, facing page 186, was taken during the last week in July, 1937, on Lake Maggiore in Ascona, Switzerland. The photograph was supplied by Alice Gulda, through the Blue Hill Meteorological Observatory. At first glance this appears to be a sort of fiery tornado spiraling its way to earth, but the explanation is simple. It is a continuing lightning stroke, such as those we have been discussing, and it was taken from a boat which rocked up and down and drifted around, so that the stroke was drawn out along a sort

of circular time axis. Thus did an amateur observer arrive at a distorted version of what we seek with our special cameras. An examination of the shore-line in the picture discloses the fact that the trees and other objects there have gone through a similar circular motion.

About the same thing happened to a picture taken from the rear platform of a train by W. N. Jennings of Philadelphia in 1892 as he was crossing a North Dakota prairie. Such phenomena are curious but also valuable, for the continuing stroke is a type to which we must give consideration in any scheme of lightning protection. These two instances show very clearly that continuing strokes occur in Switzerland, did occur in North Dakota in 1892, and no doubt are still to be found there. The important point is that a tall conducting structure like the Empire State Building is not necessarily a part of the requirements for their existence. It can be safely concluded, based on this evidence and other evidence we have taken in the Pittsfield Observatory, that the continuing stroke is one of the forms of lightning to be found anywhere that lightning is prevalent.

In general, the explosive effects of lightning will be associated with those discharges having high current values of relatively short time duration, but which will develop considerable mechanical and magnetic forces while they last. Such a discharge blows a tree apart, or distorts a coil, or crushes a tube of copper. If the dis-

charge is of the continuing type, the objects contacted by it will be burned, whether human or inanimate. An example of the latter is a sphere which for six years was unwittingly collecting data atop the radio tower of Station WSM at Nashville, Tennessee, until one day, during a violent lightning storm, the sphere came down ignominiously from its lofty perch 878 feet in the air, looking like a sieve. The size of the holes, from laboratory tests on similar metal exposed to the artificial lightning generator, were calibrated in terms of electrical charges. When Mr. Montgomery, the engineer, sent us the sphere we realized that another means of collecting data had been found.

We have included at the end of this chapter these few examples of the destruction wrought by lightning bolts, because they will make more real to the reader such terms as initial high-current discharge and continuing discharge. Daylight pictures of damage are the natural complement to night-time pictures of the bolt as it pursues its way through the air.

In closing, we might consider briefly cloud-to-cloud discharges, which occur in most storms but which seem most prevalent when clouds are high above the ground. Such strokes seem to involve much smaller currents, and this might be expected because each end of the stroke is in a cloud, where the mobility of charges is relatively low. Thunder from these strokes is not as violent as in the case of strokes to ground, but it persists

longer and is of the rumbling type. Such cloud-to-cloud strokes can extend themselves considerable distances, and are often slow enough so that their progression can be followed with the eye. They can only damage the earth to the extent that the cloud field changes, as we have seen previously, resulting in the release of bound charges on the ground. These effects are usually small, compared to the ones accruing from the direct strokes to ground.

15. THE THUNDERSTORM

IT SEEMS quite certain that the electrification of the storm cloud depends upon the action of convection currents of air, since it is known that these air currents rising from the earth separate the large and small raindrops, carrying the latter up with them, and this in turn separates the positive and negative charges within a cloud. But, whether the raindrops become electrified through their breaking up, or by their being brought into contact with each other while polarized, and thus separated again, or whether positive and negative air ions, particles bearing electrical charges, are brought into contact with polarized raindrops, is a controversial subject among the experts. To most human beings it may not be a matter of great importance, but because

at some time in their lives they have asked or will ask, "What makes a thunderstorm?" we will present here the three best-known theories of thundercloud electrification. Each one of them involves one of the methods just mentioned.

The first of these is known, after Sir George Simpson, as the Simpson "breaking-drop theory," which states that the violent upward air currents which are always present in a thunderstorm carry up moisture which condenses as it rises. The condensing water-vapor then combines into drops and these eventually become heavy enough to fall against the upward air currents. These drops combine with other similar drops, becoming still larger as they fall. Some of the drops approach a limit, which has been described as about a fifth of an inch in diameter. In a sort of continuous cycle, as the drops become larger, an increasing number are broken apart by the upward air currents and are carried to the upper reaches of the cloud.

In the breaking of the raindrops lies the electrification process of the storm cloud, according to Simpson. He believes, and has advanced laboratory experiments to support his belief, that when the drops break, negative ions are released into the air and the drops of water become positively charged. The negative ions become joined with minute cloud particles, and are carried upward with the velocity of the air currents, thus quickly being removed from the vicinity of the positively

charged raindrops. These raindrops are also carried upward, but at a slower rate, until by recombination they again become large enough to fall. In falling, they continue to grow, as before, until they are again broken up. And, as this process continues, more and more negative charges are accumulated on the raindrops. Thus, the upper and rear portions of the cloud become negatively charged, while in the restricted regions in the lower part of the cloud the positive charges are accumulated. The location of this region is determined by the velocity of the upward air currents, since the largest drop which can exist is that which can be supported by an air velocity of eight meters per second.

Simpson's theory is also supported by measurements which he has made of the electrical charge on raindrops falling to the ground. These show that as the storm clouds pass overhead, the falling rain consists first of large drops charged positively; next comes a mixture of negatively and positively charged rain; and finally, as the cloud empties out, there is a steady downfall of moderate- to small-sized drops charged negatively.

J. Elster and H. Geitel, on the other hand, have postulated a very different theory of cloud electrification, but one in which the upward air currents of thunderstorms play as prominent a part as in Simpson's theory. In arriving at an understanding of their explanation, one may visualize the carrying-up of atmospheric moisture by the upward air currents, the formation of

drops, and their combination and fall, much as in the first case.

But, say Elster and Geitel, since the earth under normal conditions is negatively charged, a separation of electricity will occur on each drop of water, because of induction, even though that drop is remote from the earth. Somewhat like a miniature cloud, the bottom of the drop will be positively charged, and the top will carry a negative charge. As the large drops fall through the upward-moving air stream, the smaller drops, being carried upward, come in contact with the lower surface of the larger drops. As the negative top of each droplet contacts the positive bottom of a larger drop, an exchange of charge occurs. The smaller droplet gains a positive charge, while losing an equal amount of negative charge to the large drop. The smaller drops continue their upward journey, gaining positive charge at each contact, while the larger drops proceed downward, gaining negative charges as they go. Thus, an accumulation of negative charge occurs at the bottom of the cloud, while the upper region becomes positively charged.

A brief description of a third popular theory of thundercloud electrification, that advanced by C. T. R. Wilson, will conclude our consideration of this subject. Wilson explains his theory by following the progress of the water drops through the rising air currents

of the thunderstorm also, but attributes their electrification to contact with air ions.

There are normally present in each cubic centimeter of atmosphere about a thousand positive and about eight hundred negative "small" ions, having mobilities of about a centimeter per second under the action of a field of one volt per centimeter. There are also present from one to sixty thousand "large" ions of much smaller mobilities. According to Wilson, these ions are greatly increased in number by the strong electrostatic fields present in thunderclouds. The positive ions travel toward the negatively charged earth with a velocity dependent upon the field strength surrounding them, while the negative ions, being of like sign, are repelled and travel away from the earth.

Obviously, raindrops falling or rising must encounter many such ions. For the electrification to begin, as in the Elster and Geitel theory, it is necessary (due to the earth's field) that each drop be positively charged in its lower part, and negatively charged in its upper section. Drops falling to the earth at a speed greater than that of the positive ions, going in the same direction, will not be overtaken by the latter. Rather the positive ions will be overtaken by the drop, but will be repelled by the positive charge on its lower surface. The negative ions will be attracted, however, by the positive charge on the drop's lower face. As the drop encounters and attaches more negative charges, it will finally

become negatively charged. As these negative charges accumulate in the lower part of a cloud, the field becomes more and more intense, and adds to the earth's field in the same degree. This increases the polarizing effect on the drops above and aids in the electrification process.

Drops which do fall more slowly than the positive ions will be overtaken by them, and as a result of the contact will become positively charged, being attracted by the negatively charged upper surface. Smaller droplets rising upward will be charged positively in a similar manner. Thus, according to the Wilson theory, and corresponding to the result obtained by Elster and Geitel, the upper regions of the cloud become positively charged, while the lower region is negatively charged.

As already pointed out, the oscillograms taken in the Empire State Building during thunderstorms show that, at least in the cases measured, the lower cloud region was negatively charged. In some three cases the more remote cloud regions were shown to be positive in their polarity.

Of these three theories none can be said to be entirely satisfactory, but Simpson's breaking-drop theory cannot be set aside because the cloud polarity does not agree with those we have measured. There can be no doubt that falling raindrops are broken up, and the laboratory tests do indicate positive drops as a result. Per-

haps parts of all three theories contribute to the final electrification of the clouds. The difficulties involved in obtaining accurate information as to the process of electrification within a cloud are tremendous, and much speculation is involved. Probably a long time will pass before a satisfactory solution is found. Meanwhile the clouds form, the rain comes down, and lightning continues to be a subject for research.

In some respects the thunderstorm has very definite and regular habits, in others it performs haphazardly. Storms will develop centers of activity which may persist during the entire time we are observing them, or they may die out as other centers become active. Storms usually travel through a given geographical region in a common direction, as from west to east, but occasionally this rule is violated. From the point of view of protection against lightning, however, it is important that this general direction of approach be established. This was noticed particularly in the New York City study.

As a rule, storms approached from New Jersey and disappeared to the east. Strokes would reach the Empire State Building at a considerable angle, while the cloud center was still over the Hudson River, more than a dozen blocks away. And as the storm passed over our theater of action, strokes would continue to strike the building, even after the storm center had passed considerably to the east of the structure. In such a sit-

uation one would be inclined to depend less on the cone of protection on the side from which the storms arrive. In the study of strokes on transmission lines it was found that, with horizontal conductors only 60 feet across, the conductors located on the approaching-storm side received the greatest number of strokes.

Of course, as we have already pointed out, the presence of a tall structure has the effect generally of increasing the number of strokes of lightning which will connect with it. This is because the building initiates strokes from its peak to the cloud before the cloud is ready to do some striking on its own account. Low objects, possibly 100 or 200 feet high, have little or no effect upon the cloud discharge, but if a discharge which is already on its way comes within the influence of such a structure, it will usually strike it.

Measurements which have been made of the intensity and polarity of cloud fields during a storm indicate that during a period of activity the field may build up rapidly to a discharging potential in as little as two seconds, followed by a sudden decay to zero. At times sudden reversals of polarity can be measured.

We have a common expression, heard many times during the summer lightning season as a storm renews its activity after a lull: "The storm is coming back!" It is quite common for several storms to follow each other through the same general region, and to one not in the position to make a good observation, an impres-

sion is received that the original storm is returning. But storms are like spent money—they seldom if ever come back.

Even the discharge characteristics vary from one day to the other, lightning strokes of a similar type such as high-current, low-current, continuing, or multiple being rather clannish and generally refusing to mix. The photographs taken in New York have borne out this tendency, showing that high-current strokes were not usually mixed in with low-current strokes, and that continuing discharges were more common in some storms than in others. In one of our reports, recording an investigation carried on at Roanoke, Virginia, is this supporting quotation: "Thus, in a total of 15 days on which expulsion gaps functioned due to lightning, multiple strokes were measured only on 3 days, but during these 3 days, 8 out of 19, or 42 per cent, were multiple." It would seem that this was no accident, and that cloud structure, broadly speaking, must have much to do with the kind of a lightning storm we experience on any given day.

On the subject of thunderstorm formation, we might say that there are, broadly speaking, only two types of storms: local storms and those which travel considerable distances. The first type can be divided again into heat and mountain thunderstorms. These obviously result from local conditions, and are usually predicted by the Weather Bureau as "local showers" or "local thun-

dershowers." Actually they may or may not develop, and such a prediction in the newspaper really means that conditions favorable to the formation of thundershowers exist, but local circumstances will determine whether or not they materialize. The weather man's score on these may not be so good.

On the other hand, the other type, which includes the cold-front, overrunning cold-front, and warm-front storms, results from widespread air movements of cold and warm air. These can be predicted with considerable accuracy.

This may be a good place to state that despite its reputation as a destroyer—and it is no hollow repute—lightning is also a benefactor of the human race. These benefits are entirely additional to those of a moral nature, which were touched upon in the opening chapter. Just how great a benefactor it is may never be known. Natural lightning produces, free of charge, about 100,000,000 tons of fixed nitrogen annually over the earth's surface. Lightning acts in this capacity the same as heavy electrical charges do in a nitrogen-fixation plant. The chemical constituency of air, composed roughly of four parts of nitrogen to one part of oxygen, is broken down by the passage of the lightning bolt, and the fixed nitrogen is deposited in the soil with the rain. In manufacturing fixed nitrogen, electric sparks 15 or 20 feet in length are employed. Nature provides a spark in lightning that may be thousands of feet in length,

thus producing great quantities of this essential agricultural chemical, although the quantity per acre is necessarily very small.

This chapter may well be closed with two more odds and ends of thunderstorm miscellany. Both concern the 10,000,000-volt artificial lightning bolt.

First, it was sent on one of the longest and strangest journeys ever undertaken by man. One of the few advantages in weather that Little America enjoys over the more temperate regions is an absence of thunderstorms, because of the extremely cold, dry air. For a brief interval on the night of April 8, 1934, this advantage was spuriously dissipated, when the members of the Byrd Antarctic Expedition were treated to a long-range, man-made thunder and lightning storm, the curious gift of the Springfield (Massachusetts) *Republican*, which took this method of pandering to the nostalgia of the expedition personnel locked behind the great Ross ice barrier ten thousand miles away. The storm lasted five minutes. The crackle and crash of 10,000,000 volts of lightning were sent through the ether by way of short-wave radio as a special wire carried the sound from the High Voltage Laboratory of the General Electric Company, at Pittsfield, to the transmitter. Thus Admiral Byrd and his men were able to experience all the "discomforts of home" without getting wet, for the "clouds" which provoked the

storm were laid neatly along ladder-like racks in Pittsfield's steel-vaulted laboratory.

The second piece of miscellany concerns a journey of time rather than of space. Unless there are some rather radical changes in the scheme of things, lightning will probably exist in its natural state 6000 years from the present, but just to make sure that people living in that future age miss none of our modern sensations, Oglethorpe University has sealed in its buried "crypt of knowledge" a piece of film on which the 10,000,000-volt discharge has been recorded, along with such other things as maps, photographs, newspapers, and a microtext of the entire Encyclopædia Britannica. The inscription plaque on the door of the crypt requests that the contents remain sealed in the chamber until the year 8113, a date selected by Dr. Thornwell Jacobs, President of the University, because when he began the project in 1936, the year 8113 was just as far into the future as the total number of years in which man has recorded events of the past.

16. FOLLOW THE LEADER: SOME CASE-HISTORIES

IF THERE is any one thing to be learned from a study of lightning's case-histories, it is the importance of a good ground in the protection system, whether it be lightning rods or communication or power systems. Lightning is frequently accused of performing "freak stunts," which appear to the usual observer as freaks, but which to lightning are the natural thing to do. After all, lightning obeys natural laws, and when it performs seemingly strange pranks, the reason for its performance can usually be found in the evidence, providing the necessary clues are still available when the trained investigator arrives on the scene.

Before beginning these brief case-histories which we

have selected as typical relics of a thunderstorm, the reader, and especially the rural reader, might well run over in his mind the setup of his own home. With whatever information regarding the habits of lightning that he has accumulated in the preceding pages he may be able to put his finger on one or two weak or vulnerable spots, and thereby save himself some future trouble. And, if he can think of none now, perhaps he will before he finishes this account.

The tales that are passed down through the generations of any family usually include two or three having to do with lightning damage, particularly if that family has lived on a farm. Most of the questions which they raised have never been solved because of a lack of informed investigation at the time of the occurrence. Yet with what we know today regarding the generation and transmission of the lightning stroke, most of these occurrences could have been explained. Many of the cases for which explanations can be found add to our store of knowledge, and often such knowledge is of great value. Lightning investigation, while it teaches us many things, always has a flavor of the anti-climactic. Often, when we arrive on the scene, the barn has been burned, the tree has been destroyed, or the human being involved in all too many cases has been severely injured or killed outright. However, we go over the ground like a Sherlock Holmes, pursuing the available clues and discovering, if possible, what happened.

In the first case to be mentioned here lightning struck through a large elm tree standing in front of a country home, jumping from the tree to the house, and making its entrance just below the eaves. The discharge passed through the wall and entered the top of an iron bed in which a man was asleep. He was unharmed. From the bed the stroke passed into the floor, and through it to a stove in the kitchen just below. Part of the discharge found its way to a ground by jumping across the kitchen from the stove pipe to the ground rod that had been installed by the telephone company. It happened that this was the only good connection to ground to be found in the house. The barn in back of the house was burned, but whether this was the result of the same stroke or occurred as the result of a separate discharge is not known. Probably the former was the case, since house and barn were connected by a radio aerial. At any rate, the results were one barn burned and one man frightened but unharmed.

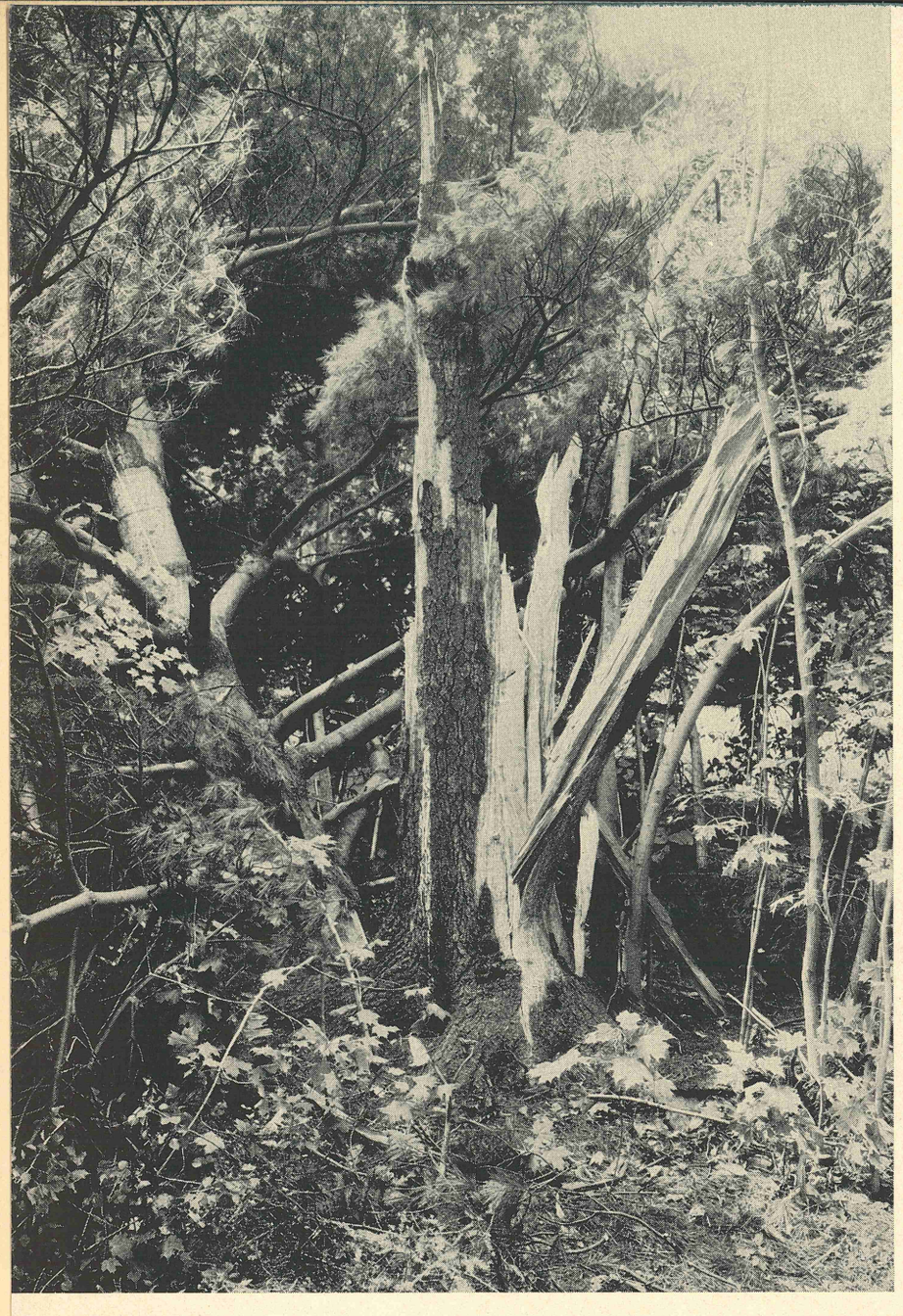
The man was sleeping in a metal bed, for which he has cause to be thankful. The difference in potential created between the head and foot of the bed was not sufficient to divert any part of the discharge to his body. He might not have fared so well if the bed had been made of wood, since there would have been more chance of the discharge passing through him on its way to the metal springs and thence to ground.

There is no evidence that the elm tree played any

part in directing the stroke, since only the extreme ends of some small branches were involved. Apparently the stroke would have taken the course it did even if the tree had not been present. The tree was twice as high as the house, and some of the branches hung over the house. Evidently trees cannot be depended upon to divert strokes from near-by homes even if the structures are within the cone of protection of the tree. It is believed, however, that if the tree in question had been provided with a well-grounded lightning rod system extending up into the uppermost branches of the tree, the stroke would not have made contact with the house—it being within the cone of protection of the lightning rods in the tree. There is some reason to suspect that the conductivity of trees may have something to do with the likelihood of their being struck. The tree which is able to produce streamers from its top is more likely to be struck, other things being equal.

The question has been asked often as to whether lightning is ever guided by a tree to its destructive rendezvous without actually entering the tree. This question is answered by the following case, illustrated on page 187. In this instance both actions occurred, but the point is made nevertheless. A lightning discharge struck a 60-foot pine tree on the shores of Pontoosuc Lake, near Pittsfield, and for a distance of 40 feet it followed the outside of the tree, leaving as evidence of its passage a compressed streak on the bark. This

Continuing lightning flash taken July, 1937, on Lake Maggiore, Switzerland. Motion of boat during time camera shutter was opened produced unusual appearance shown. Supplied by Alice Gulda through Blue Hill Meteorological Observatory.



Stroke to 60-foot pine tree. Discharge followed outside of tree for 40 feet, compressing bark and leaving visible streak. About 20 feet from ground lightning entered tree, blowing it apart so quickly that upper portion was found standing upright beside stump as though it had grown there. Later it tipped, as shown in picture.

was caused by the great pressure of the lightning discharge, and no signs of burning were found. At a point about 20 feet from the ground the bolt entered the tree itself, and blew it apart so fast that the upper 40-foot section dropped into a vertical position beside the shattered trunk just as if it had grown there. By the time the photographer arrived to take the picture shown in this book, however, the upper section had tipped over to a slight degree, making an angle of about 30 degrees with what remained of the trunk. This instance indicated two things: the great pressure of the discharge in making the streak and then blowing the tree apart, and the rapidity with which the effect was produced, testified to by the manner in which the section dropped straight to the ground. Since there was pressure and no burning effect, probably the result was caused by a high-current discharge with little or no continuing current.

On the other hand, photographs were also made of another pine tree, evidently damaged by a stroke which began with a heavy, high-current, short-time discharge, followed by a continuing discharge with or without peaks. The upper 50 feet of this pine tree were lying on the ground, with about ten feet of the stump remaining. Although there was no sign of burning on the fracture of the trunk lying on the ground, the stump of the tree had burned so that a near-by neighbor put out the fire with pails of water. Apparently the

tree was blown apart near its base by the high-current discharge, and the burning began after the trunk had been blown out of the path of the bolt.

Of additional interest about this instance is the strange path taken by the bolt after it had destroyed the tree; and yet there is nothing strange about it in view of the facts known. First, a splinter of the original tree was blown through the bark of another tree standing 30 feet away. Second, the path of a small stream of water near the base of the original tree was altered by the discharge. This effect was brought about as a result of the lightning discharge following out the root system of the tree in the direction of the stream. Finally, damage was found in a cottage several hundred feet away. The discharge, after altering the stream's course, and following it to a nearly buried pipe, apparently came up out of the ground at a point near the screen of the cottage's screened-in porch, and eventually went to ground over the electric light and telephone systems to complete its strange journey. Apparently the buried pipe was located near the corner of the porch where the damage began, and the tree was known to have involved the pipe, hence our deduction as to its course. It is possible that another discharge came in over the lighting and telephone systems and then went to ground, but in the light of the other facts, this was thought not to be the correct explanation.

As many have observed, lightning can plow a pretty

good furrow, and this effect is found many times. We might mention a typical case and then explain the phenomenon. In this case a tall tree, rising about 90 feet from the ground, was struck. The furrow, or path, several inches wide and 50 feet long, extended from the base of the struck tree to another tree to which telephone wires were attached. The discharge then traveled up the tree and along the telephone wires in either direction from the point of contact, damaging a telephone cable at one end and a subscriber service at the other end, all in an effort to reach a good ground. So much for the result itself.

If one could have observed this event from a safe distance, he probably would have seen something like the following, if we base our conclusions on what we have learned about the mechanism of the discharge in the preceding chapters. As the downcoming stepped leader approached the ground, streamers began to form from the trees located in the woods, where the bolt eventually struck. Perhaps the streamer from this tree was longer than the others, and served to guide the downcoming leader to itself when the leader was a few hundred feet away. Down on the earth, meanwhile, charges had been accumulating—slowly at first, and then with greater rapidity, as the field created by the downcoming leader became more and more intense. No doubt all around the base of the tree there were long streamers, reaching out in all directions and looking

for a source of positive charge. Finally, one of these thin blue streamers reached the tree supporting the telephone wires. Probably other streamers were extending from the wires down the pole, and when the two met, a large source of charges became available because of the good ground on the telephone protective system. As contact between the downcoming leader and the streamer up from the tree was made, positive charges rushed from the telephone wires, across the intervening earth, up the tree, and into the lightning channel. It was this rush of charges which plowed up the furrow in the ground and then split the tree. Where charges on the ground are easily available, the damage is confined to a small area, but when they can only reach the lightning contact point with difficulty, then high voltages appear which break down insulation, jumping from one point to another to complete the path. In this case they left an actual path, not an invisible one. If soil happens to be of sand, or of some other poor conducting type, the lightning current is quite likely to travel along the surface of the ground, after once entering it, to seek a path with less resistance.

Several other cases have been observed where strokes came up out of the earth to find a better ground. The next case to be described is also one of that type. There is reason to believe that strokes occurring to the earth, not too far away from power lines, will find a path to ground by passing up the tower and going to ground

by way of the overhead ground wire. Such a stroke, if negative, will register as a positive discharge on the magnetic link because the direction of flow of the current has reversed. In this manner a certain number of so-called positive cloud strokes may be accounted for.

One of the most obscure, and at the same time most interesting, cases to come to our attention was one which resulted in the death of a young man at a Civilian Conservation Corps camp. There was a storm and the boy, standing beside his bed, looked out of a window; there was a flash of lightning and a simultaneous crash of thunder—and the boy was found to have been killed; the only burns were on his chest and right leg. How was he killed, when an examination of the building disclosed that it had not been struck by the lightning discharge and that he was not close to wires of any sort?

We made a careful examination of the premises and established certain facts. Eventually there was found a small burn, about the size of the lead in a lead pencil, in the floor under the place where one of the legs of the iron bed had rested. Later, when the tar paper at the base of the building was torn away, it was found that the wooden siding near the window, where the youth had stood, had been split by the lightning discharge. Between this point and a small scrub apple tree 25 feet high, which stood near by, there was a path, but whether it had been caused by a lightning stroke or by a stream of water resulting from the storm could not

be established. There were traces on the tree which indicated that a lightning discharge had come down it, and we surmised that what had happened was that lightning had struck the tree, and that the discharge, following the path we found, had traveled to the building, up through the floor, into the iron bed, and into the right leg of the boy as he stood by it looking out the window. But what about the chest burn?

We noticed that between each pair of windows in the building a wooden shelf had been erected to hold personal effects. When the boys were not eating, an aluminum plate about ten inches in diameter was customarily hung on either end of the shelf. One of these plates had played a role in the tragedy. The shelf was at such a height that the lightning discharge, having entered the boy's leg, passed out through his chest into the plate, thence through a ten-penny nail, burning its point, and then to a window screen. From the window screen it jumped a gap a few inches long to make contact with an unused radio antenna under the eaves; it followed the antenna for a distance of approximately 50 feet, then jumped to an electric light circuit inside a building two or three feet away. The discharge then followed this circuit to the captain's quarters, located probably 100 yards away, and there at last it achieved its first connection to ground after leaving the earth under the building where the boy was killed.

The captain had draped his telephone cord over the

metal support of a bridge lamp to keep the cord out of the way. We found many burns on the metal of the lamp, and corresponding burns on the telephone cord. It is customary, in the case of each telephone installation where water pipes are not available, to drive a pipe into the ground for an earth connection. This is then connected to the telephone lightning arrester or protector blocks. The fatal discharge which we have been following had gone to ground largely over three of these protector blocks, located at varying distances from the barracks where the young man was killed. An estimate, based on the appearance of these blocks, indicated that a total current of perhaps 30,000 amperes had passed through the boy's body.

The question might properly be asked as to why the discharge did not stay in the ground at the base of the tree, and to answer it we must go back once more to the mechanism of the lightning stroke, remembering that we are not dealing with a single lethal charge hurled out of the sky, but with a pre-stroke condition in which complementary charges of opposite electrical sign are being concentrated in the earth as a preliminary to completing the circuit. Probably the ground around the tree would have carried a current of the order of the estimated 30,000 amperes, but the ground resistance was so high—or the availability of charges so low—that a very considerable voltage, perhaps several million volts, appeared between the base of the tree and the

circuit consisting of bed, boy, plate, screen, aerial, secondary light wires, and telephone wire to ground. The latter, being another source of charges (as were the telephone wires in the previous case), allowed lightning current to flow and it killed the boy.

It is not often that lightning comes up through the floor. The boy would have been safe enough if he had been in bed, but he happened to be in a position where the discharge passed through him on its way from bed to eventual ground. It is probable that most of the ordinary precautions taken would not have prevented this fatality, but it is possible that if the barracks had been provided with well-grounded lightning rods, these would have been struck instead of the tree, and the youth would not have been involved. This stroke illustrates clearly once more just how far a discharge may travel to reach a good ground, and how unforeseen and widespread the effects may be if a good ground is not available at the point struck.

Incidentally, these cases illustrate also the three main hazards of standing under a tree during a thunderstorm. First, the discharge may side-flash from the tree; second, in passing through high-resistance soil at the base, it may pass considerable current up one leg of an individual and down the other (often the reason why cattle are killed under trees); third, the tree may explode and hurl flying debris, injuring persons beneath it.

A final story of lightning damage will remind the

reader of some of the laboratory experiments with man-made lightning which we have dwelt upon, and will also serve to show lightning's versatility in the face of what might be thought good protection. The damage occurred in a home that was provided with a lightning rod system, but the lightning did not strike the system. Rather, it struck a tree in front of the house and about 85 feet away from it. The owner of this home, which was located in the country, was engaged in operating a tea-room and, indirectly, it was his industry which caused the trouble.

To advertise the tea-room a sign had been placed on the big tree out in front, so as to be visible from the road. For illumination at night the sign was lighted by an electric lamp placed above it on the tree, and connected to the house wiring system by a length of parkway cable buried 10 or 12 inches under the ground. Power was supplied to the tea-room from a transformer located on a pole across the road from the house. A telephone drop-wire, consisting of two No. 14 copper wires, extended from the pole to a corner of the house opposite from that where the buried parkway cable entered the basement. The telephone had been provided with the usual protector-block installation and a driven ground rod. On its way to the house, the telephone wire passed about 16 feet from the tree which carried the sign.

After the telephone had originally been installed, a

rather extensive private water system had been placed in service in the home. Therefore, ground connection for the telephone was not made to it, but when the electric light circuit was installed at a later date, connection of the neutral wire was made to the water pipe. As a result, the electric system had not only a different ground from the telephone system but a better one.

Lightning struck the tree, causing a certain amount of damage in the house which was protected by a lightning rod system. Question—where was the Achilles' heel? The stroke was to the tree in front, and immediately it was noticed that the parkway cable connecting lighted sign and house, consisting of two No. 14 wires inside a lead sheath, had been completely vaporized and had blown out the earth, making a trench extending from the tree to the house. No trace of the cable could be found at all between the base of the tree and the point in the house, 85 feet away, at which it came in contact with the water pipe. Beyond this point, the cable was not damaged at all.

We made tests in the laboratory with a similar piece of cable and an impulse current of more than 200,000 amperes, and eliminated the lead sheath. We were never able to vaporize both the sheath and the conductors, as had happened at the tea-room. It may be that the damage was caused by a multiple stroke with discharges of high magnitude. We learned also that the telephone wires were burned up from the point where they passed

through the tree to the pole across the street. The insulation on the conductors was never found. In the small branches of the tree, in the general direction of the discharge and the location of the telephone wires, there were indications that lightning had passed. It seemed likely that both telephone wires and parkway cable were destroyed by successive discharges in the same stroke.

A much smaller current must have passed through the telephone wires in the direction of the house, because in this direction the telephone wires were not destroyed. And in the house, just back of the mounted telephone protector blocks, was the screen from a screen door, removed a few days before. Lying over the screen was an electric extension cord, plugged into a baseboard outlet which brought the water-pipe ground close to the screen.

As might be expected, we found that some of the lightning stroke had passed through the wall from telephone system to screen and thence to the extension cord, from which it went to ground. Lightning current had flowed into the driven rod which formed the ground for the telephone system, but sufficient potential developed to allow a spark to jump to the extension cord.

This could have been prevented by connecting the telephone and lightning systems to the same water-pipe ground. The stroke was principally remarkable for its

ability to destroy 85 feet of lead-covered cable without enough current leaking off the conductor to prevent the destruction of the entire cable length. It means that burying an 85-foot parkway cable 10 inches in the earth does not necessarily represent a satisfactory ground. The case also illustrates the desirability, from the point of view of lightning protection, of connecting together any ground connections which might carry a lightning current, thus preventing a discharge between them.

That, in turn, serves to recall the story already mentioned of the man who lived in the cottage at the base of a mountain. He amused himself during thunderstorms by watching sparks jump between the water faucet and the sink in his kitchen. It will be recalled that the water came through a partially exposed pipe from a spring up the mountainside, and that sufficient bound charges were frequently released on the pipe to produce the sparks. The remedy, of course, would have been to bond the sink and faucet together. It would have spoiled the show, but would have made the kitchen a safer place in which to sit.

In any country home, therefore, where water systems have been installed, it is wise to have the grounding situation checked with respect to the telephone and power circuits. In the case of the tea-room, a further precaution would have been to connect the lightning rod system also to the water-pipe ground, in addition

to its other grounds, to prevent a possible discharge between differently grounded systems.

Perhaps the most valuable lesson that the reader can learn from this chapter is to think of lightning in terms of its *complete circuit*. Effects of lightning discharges will be confined to a small area only if the ground resistance is low at the point struck. Danger lies underfoot when lightning strikes close by—although most people probably feel that if they are not in the direct path they are safe—and in general this is true. Much is to be learned from studies of cases of lightning damage, since in this manner we are better able to predict what may happen in other situations, and how better to guard against lightning effects.

17. LIGHTNING RODS

THE lightning rod is probably one of the oldest electrical appliances known to man, since it was invented and placed in service long before electric current was generated and transmitted for human use. In Benjamin Franklin's day this electricity which was made available to the earth at no cost was not exactly a welcome commodity, and the service which the lightning rod performed—or was thought to perform—was to reject the gift as thoroughly and speedily as possible.

We have touched briefly upon the role of the lightning rod salesman in commercial history, and noted that the purchaser was left at least no worse off than before the salesman's visit, except for having made a modest expenditure.

But lightning rods today are a very serious business. When properly installed they afford a high degree of protection, and may save many times their cost in fire prevention alone. It will not be difficult for the reader, who has explored with us the processes of the high-voltage laboratory and the antics of lightning along transmission lines and atop the Empire State Building, to understand both the basis and the need for lightning protection systems. It is only fitting that we add here a few words about today's lightning rods and their applications.

The likelihood of lightning striking buildings in the open country is much greater than it is in the city, because the exposure in the country is considerably greater and because of the absence of higher buildings to divert the stroke. City dwellers are fortunate, from the lightning point of view, in being crowded together in honeycombs of steel and stone which more or less shelter them from harm. If something does happen to them, they have all the advantages which a closely knit and well-organized community affords in the way of assistance.

The type of construction ordinarily used in the country is such that it is more vulnerable to the after-effects of lightning. The houses and outlying buildings of wooden frame construction are inflammable, and so exposed that a fire, once started, is fanned by wind and is difficult to control. The risk of damage to life and

property is much greater in the case of the rural structure. Fire-fighting machinery and ambulance service may be miles away, and the water system on the farm inadequate.

The United States Census Bureau reports show that nearly 2000 people are killed or injured by lightning in the United States each year. Statistics over a number of years indicate that nine-tenths of these lightning casualties occur in rural areas, and in towns and villages with a population of 2500 or less.

A 10-year survey in the Province of Ontario, in Canada, disclosed that during the period covered, 10,079 lightning fires took place in structures not equipped with lightning rods, while only 60 such fires occurred in buildings with lightning rod systems of protection. Of these sixty fires, it was found that many were started in structures equipped with improper lightning rods, or rods in bad condition because of poor maintenance.

It is safe to say today that a lightning rod system practically eliminates the chance of damage from a stroke, although it will not prevent the stroke itself. Some slight electrical discharge may occur from the points of the rods preceding the discharge from the cloud, and some have thought that this tends to prevent the stroke. Readers of the preceding chapters will know better, however.

Lightning rods do not "draw" lightning—another superstition that is popular in the country. A rod pro-

jecting but a few feet above the roof can have little to do with drawing the stroke to a given house from a cloud that may be 1000 feet above it. It is true that the effective height may be extended somewhat by the formation of streamers just prior to the completion of the stroke path. We have seen that the Empire State Building and comparable structures of great height tend to act as needle-point electrodes and initiate strokes with upward leaders, but the lightning rod on "Farmer Brown's" barn is a far different matter.

The principal function of the lightning rod system is to make a skyscraper out of a country building, or, in other words, to make the wooden rural structure perform during a thunderstorm like a metal structure. The system receives the lightning stroke and discharges it harmlessly to the conducting earth. To do this it must be correctly installed. Obviously the rod alone would perform no such feat. Often occupants are not even aware that a well-protected structure has been struck, although they will know that the stroke was close since the lightning and thunder will be practically simultaneous.

An all-metal roof is not to be considered as suitable protection unless separate sheets are thoroughly bonded together and suitably grounded. Holes may be burned in a metal roof which would have been prevented by the installation of lightning rods.

From the foregoing it becomes plain that the installa-

tion of lightning rods is extremely important, and is a task that should not be left to irresponsible or inexperienced persons. A faulty system might well prove more dangerous in a storm than none at all. The voltage of a bolt varies with the length of the stroke, and a stroke may range from 100,000,000 volts to 10,000,000,000 volts. The current varies in different strokes from as little as 2000 amperes or less to 200,000 amperes. The time duration of the high-current peaks is very short, but we know that there may be a number of discharges which appear to the eye as a single stroke, and it is when such a number of discharges occur in rapid succession, with continuous current flowing, that a fire is most likely to begin.

When an object is struck by lightning the voltage on that object may increase at the rate of 1,000,000 volts or more per millionth of a second. However, as most objects struck by lightning are less than half a millionth of a second (500 feet or less) from ground in terms of lightning speed, potentials of over 1,000,000 volts seldom appear. The current to ground may increase at a rate as high as 10,000 to 20,000 amperes in the same microsecond. It is the suddenness with which these voltages and currents appear, as well as the magnitude of them, which causes lightning damage, and the harnessing and taming of such phenomena is hardly within the province of the rural handyman.

With a current in the neighborhood of 100,000 or

more amperes passing through a lightning rod system, only the best ground connection will afford protection. Such a current is a billion times that which flows in the ground of a radio receiving set. Objects grounded for ordinary values of current, as we saw in the cases quoted in the preceding chapter, may assume high voltages above ground for the enormous current often associated with the lightning flash.

It has been found in the laboratory that a potential of approximately 100,000 volts is required to jump a distance of one foot. If this value is applied to natural lightning, a flash from a 1000-foot cloud would require a voltage of 100,000,000 volts.

The single stroke, not multiple and not continuing, has been called "cold lightning," but the term is to be taken with a grain of salt. Because the time of a single discharge is so short, it will not ordinarily start a fire, since the discharge is often completed before wood has had time to ignite. However, barns containing hay are often fired no doubt by a single stroke because of the comparative ease of ignition.

We have been discussing lightning rods in connection with rural structures because the latter are the most vulnerable, for reasons stated, but protective systems are not confined to this class of building. Many lightning rod systems are installed today to protect unusually fine trees on estates and in parks. And even the city skyscraper, which we have designated a natural light-

ning rod, may be found to need protection against the elements.

One such example is the General Electric Building in uptown New York City, a 48-story structure which raises a Gothic tower more than 600 feet in the air. It affords a good illustration of the point that even a modern all-steel skyscraper is not made lightning-proof because of its steel frame. The building, when new, was known to have been struck and damaged on three occasions. Investigation disclosed that the steel work had not been carried to the upper extremity of the tower, and that it was capped by 50 feet of brick and terra cotta with non-grounded reinforcing members.

It happened, on the occasions mentioned above, that lightning strokes seeking the path of least resistance had passed through portions of the masonry. Blocks of stone and terra cotta and bricks were thrown in all directions, some of them landing in the street below. In a few millionths of a second considerable damage had been done, but the danger was not to the people in the building, but rather to persons in the street below.

It was decided to provide metal paths around the upper brickwork, and the tower was equipped with a lightning rod system which would conduct bolts of lightning harmlessly to the ground, without danger either to the structure or to its occupants. Today the building is one of the safest places that New York City affords in a storm, and even the inhabitants of its forty-

eighth floor are not aware when it has been struck by lightning.

With the installation of the system a certain amount of protection was also offered to near-by lower structures, including the adjacent St. Bartholomew's Church, through the operation of the principle of the cone of protection. A low lightning rod is particularly effective in this respect in proportion to its height, as laboratory tests show. A rod 100 feet high is assumed to protect a flat area surrounding it for a distance of approximately 200 feet from the rod's base, when a storm cloud is not lower than 1000 feet. A 500-foot rod will protect a distance of approximately 650 feet, and a 1000-foot rod will protect a distance of at least 1000 feet, assuming a flat area. Structures within such protected areas should not project their uppermost points through the imaginary cone drawn around the protecting rod, the apex of the cone being at the upper extremity of the rod and the base having a radius equal to the distance protected at ground level.

Several times the Equitable Building in New York City has been struck. In one instance, before protective measures were taken, in lightning's frantic effort to reach ground it chipped off a large chunk of stone and bounced it into busy Broadway below. As this was rather hazardous, we were appealed to for some method of protection. A frequently grounded copper strip encircling the top of the building was installed, and ever

since that time lightning has been discharged harmlessly.

If they are properly installed on a home or other building, lightning rods, according to our available records, will reduce the chance of lightning damage to less than five per cent of what it would have been if the structure were unrodded. The actual performance record is probably better than that figure, but five per cent is conservative. Rules governing the installation of lightning rods have been prepared and may be obtained from the Superintendent of Documents, Washington, D. C.

In an installation the number and location of air terminals is important, as is also the number of down-conductors. The down-conductors should find their way to ground with as short a path as possible. Grounds are of paramount importance, and a few dollars spent in getting low ground resistance will be worth while. If an extensive water system is available, connection should be made to it where permissible. Where the system is not extensive, local conditions will govern what ought to be done. It cannot be urged too often, or too strongly, that lightning rod systems be installed by reputable installers, so that a reduction in insurance rates may be obtained in those States where such reductions are granted.

Lightning rod systems are extensively used to protect ammunition dumps, and frequently two separate

systems are used—one inside the other. Reservoirs for the storage of oil are often protected by lightning rods which take the form of masts, and make use of the intersection cones of protection. Wires may also be strung across the tanks and connected to the towers. It is important in such cases that pipes entering the protected area be interconnected or bonded to the protection system, since a difference of potential may exist during the time of the lightning stroke of sufficient magnitude to cause trouble. The same principle is back of the requirement that other conductors within a protected home either be three or more feet away or else bonded to the lightning rod system. This is illustrated by the case of the man who installed electric light wires in the attic of his home, only a few inches away from the previously installed lightning rod system, but separated by wood. Along came lightning, and, due to the high rate of current rise, developed sufficient potential to jump through the wood of the attic and start a fire. This occurrence was not the fault of the lightning rod system. The two systems were not far enough apart to avoid trouble. If several different grounds exist in the same protected structure, they ought to be bonded together, unless other considerations prevent. Many people still think that the lightning rod belongs to a bygone day, but an inspection of farm buildings, particularly in the plains States, will prove that this is not the case.

Originally it was thought that the lightning rods must be insulated from the house, but today, in new buildings, the down-wires may even be placed within the partitions with safety—assuming of course that proper conductors are used.

18. SHAKE HANDS WITH LIGHTNING

TO THE reader who has pursued these pages, lightning in either its natural or man-made state should not now present too many mysteries. The answers to almost every question can be found by referring to the descriptions of its characteristics. By applying the measuring stick, and obtaining a full-length identification in terms of volts and amperes, inches and microseconds, we have endeavored in some measure to reduce the mysterious and awe-inspiring phenomenon to a calculable force. There have been glimpses of Franklin, Steinmetz, Peek, and the others of the group who were surfeited with lightning's unchallenged depredations and determined to face it with effective weapons of their own devising. Without becoming too involved in

technical terminology, we have attempted a guided tour along transmission lines, into laboratories, up to the clouds where streamers were forming, and down to earth where electrical forces were preparing to receive the bolt and reply in kind.

Perhaps the authors have seemed to apologize too readily for the unavoidable excursions into the realm of electrical measurement and engineering practice. To some, the explanations of electrical and physical action will seem too elementary. To others, the pages will remain obscure and unsatisfactory as a portrait of lightning's flash and roar. But lightning, racing to the earth in fractions of a second, is fortunately not faced with the task of explaining itself in words of common coin, or it would find, as we have, that while a Dr. Johnson may shine and sparkle, a Boswell must stammer and sweat over his pages.

Implicit in the mechanism of the lightning stroke is the explanation for most of the freaks it perpetrates. Just to test our theory that most popular questions regarding lightning can be answered by a reference already given, let us consider a few such queries at random.

To begin, take the matter of *connecting wires to trees and poles* from a residence. Should it be done, and what may happen? There was the tea-room proprietor whose acquaintance we made some pages back, whose house was damaged indirectly as a result of his lighting

a sign on the road in front. There would have been nothing wrong in putting the light in the tree if a suitable path to ground had been provided, but not by way of the cable supplied to furnish electricity to the lamp in the tree. Before, he never gave lightning a thought, but a stroke early one Sunday morning made him very conscious of his improper installation. Trees are often used for attaching a radio antenna which extends out from a house. This is a hazard to the degree that lightning is more likely to strike the tree because of its height, and thus be guided along the aerial to the home. The chance of such damage is minimized if the antenna is well grounded, and the conductor used is large enough so that it will not be destroyed by the stroke. It is always safer, however, not to connect wires to trees, even if they pass underground as in the case of the tea-room.

What is heat lightning? Most persons employ the term when they see a general illumination or sheet-like flash of light off toward the horizon, on a summer night, and do not hear thunder. What they are seeing is not a peculiar type of lightning phenomenon, but simply a storm that is far enough away so that the sound of thunder does not carry to them. And because of this distance, the path of the stroke is obscured.

We are often asked *if windows should be closed during a storm* in order to keep out a lightning flash. The most obvious answer is that both windows and

doors should be closed to keep out the rain, which is more likely to cause annoyance than lightning. It has been thought by some that lightning discharges tend to follow drafts of air, and we have already indicated in this book that wind can blow the path of a continuing discharge as far as eighty feet under certain unusual conditions. However, a lightning discharge that was being blown would be blown into a house through the walls just as quickly with windows and doors closed as with them open, and any openings into the house would have little or no effect on the final result.

Is it safe to play the piano or sew with a needle or sewing machine during a lightning storm? Storms do not, as a rule, last very long, and while in most cases one might play or sew with impunity during the electrical storm interval, there are certain good reasons for not doing so. Why not wait a few minutes to perform these tasks? The answer to the original question depends upon two things: the size of the metal object one is in contact with, and whether or not that object is an isolated piece of metal or is connected to ground in some manner. For instance, *sitting on a radiator* is bad practice, if we may be allowed to enlarge the original question. The radiator is connected to ground through its pipes, and lightning might pass through the body of the sitter on its way to the grounded radiator in the event that the building were struck. In the case of the piano or sewing machine, a large metal object is in-

volved, and it could readily acquire a large induced potential—bound charges which would be released at the moment of the lightning stroke near by. We discussed such a situation in connection with the chapter on the induced stroke, pointing out the danger in relation to oil tanks and other unbonded and protruding structures. As for sewing with a needle, the object is so small as not to have much effect one way or the other. Size is the controlling factor here. If one were holding, instead of a needle, a metal fish-pole vertically in one hand, that would have to be considered dangerous, because the chance of being struck is increased.

Is it safe to stand in front of a fireplace? Chimneys are struck quite often in the course of a thunderstorm, because of their elevation, and because apparently the chimney is likely to afford a good conducting path. The soot in a dirty chimney, however, often turns out to be a poor conductor, offering resistance to the path of the discharge. The result is that the chimney may be blown apart, as a by-product of the increased pressure. This happens in many cases. Assuming that the discharge does follow the chimney down to the fireplace, and then jumps to a near-by radiator on its way to ground, one may be injured by the electrical discharge if standing on the hearth. Or, if the fireplace is damaged by explosion, one may be injured by the flying debris. So, standing in front of a fireplace is not too

good, either. It is to prevent this type of occurrence that lightning rods are installed on chimneys.

Handling the telephone or radio apparatus during a storm is something to be avoided as a general rule, although, once more, in the majority of instances there are no harmful effects. Since we are concerned with possibilities rather than probabilities, however, such actions deserve a warning. A good rule is not to handle any electrical appliances. In localities where wires are placed underground, the opportunity for trouble is very remote indeed, but where the wires are exposed it is safer not to use such equipment in the sense of handling it. By this we do not mean that one should not turn on or off the lights during a storm, but to keep away from wires and to limit the turning of switches to a minimum. A radio antenna is not more likely to be struck if a radio is in use. As in the case of the open windows, common sense supplies the rule, for the storm will cause so much static that reception will not be good anyway.

Taking a bath in a tub or shower in a steel-frame building such as a modern apartment house or hotel is not considered dangerous, but in the average home it should be avoided during a storm. If the bathroom vent pipe were to be struck, one might be in serious trouble; or strokes to ground at some other point in the house might include the bath tub in its passage.

Along the same lines, *one of the poorest places for*

the human being to find himself in a storm is in swimming or enjoying any form of water sport. If one is bathing or canoeing, he had better paddle to the shore and watch the storm from a safe distance. Many persons have met their death by neglecting this rule. If lightning should strike near by, a person in the water might lose his life by drowning, first having lost consciousness because of the lightning current flowing through the water. Many have thought in the past that lightning does not strike the water, but there is plenty of evidence to the contrary. The chance of a person being struck directly in the water is probably not very great, but the area of danger around a stroke to the water may be considerable. This results from the flow of current through the water from a near-by stroke which may have a considerable magnitude. Therefore, one should play safe and stay out of the water during a thunderstorm. In fact, *try to stay dry*.

Where is the safest place in the home during a storm? This is probably the most popular question ever asked about lightning, and to supply the most correct answer is to court smiles, for the safest thing to do is to jump into the refrigerator or the furnace. Unfortunately, neither of these places is habitable. The furnace, or the modern electric refrigerator is, in effect, a solid metal room, which makes it ideal as a shelter. Passing up these two alternatives, it is suggested that an individual simply carry on with the ordinary routine of living, but re-

main away from overhead wires, keep away from the radio, refrain from taking a bath, be chary about using the telephone, and keep away from metal objects of appreciable size. However, one runs little danger, and many people are willing to take chances. Some of the old ideas about lightning protection are really sound after all.

The principle of protection depends upon keeping all parts of the body at the same potential, or voltage. This may be accomplished, as we have noted, by enclosing oneself in a metal cage. This cage, in principle, is known as a Faraday cage. It is not necessary that the cage be grounded, if one stays inside of it until the discharge has ceased. Thus, to forget the home for the moment, an all-steel automobile becomes a very safe place to be, even though it is insulated from the ground by its rubber tires. But, if one steps out while a voltage exists between the car and the ground, as might be the case in an accident where high-tension wires fell on the car, one's feet would create a conducting path from the car to the ground, which might well be disastrous.

Usually, in suburban homes, very little damage results from lightning, partly because of the shielding by other structures, which reduces the number of hits, and partly because of the rather considerable number of wires, pipes, and other conducting objects in the walls, all of which form more or less conducting paths to ground and limit the extent of the damage. And in the

city, when lightning causes fire, help is usually near at hand. In the country the conditions are different, as we noted in the discussion of lightning rods. Homes are more exposed to strokes, help in fire-fighting is far away, the houses do not have as much metal in them, and water-pipe systems are not always available. Barns, too, are vulnerable to lightning, because they have little or no conducting material to ground in them. Incidentally, the city water system with its underground ramifications represents an excellent ground from the point of view of lightning.

With both the furnace and the refrigerator out of consideration as places of refuge in a storm, perhaps the iron bed, with a projecting head and foot, marks the nearest approach to complete safety. If the sides of such a bed are kept away from the wall, and if the occupant will stay on the bed—that is, not hang an arm or leg out—he will survive most strokes to his home without personal injury. We have recently run across several instances where persons in iron beds were not hurt even where the lightning discharge passed in the head of the bed and out the foot where it rested on the floor.

Radio antennas are struck by lightning occasionally. How frequently is not known, but probably not often enough to represent any great hazard. In Pittsfield, Massachusetts, where the lightning laboratory is located, about one antenna per 10,000 homes is involved each year. For rural installations, this percentage is probably

higher, in many of the cases the antenna being attached to a tree; which, as we have noted, will lead the lightning discharge to the house. Since an antenna is made of rather small wire, it is often destroyed by the lightning discharge, with the result that contact with the ground is lost and lightning is free to do a certain amount of damage as it seeks its own way to ground. This situation can largely be avoided if at the point of attachment to the house a heavy, well-grounded conductor is brought close to the antenna, forming a gap of about an inch. Or, if a lightning rod system is available, the antenna may be brought into close proximity with it. Then, if the antenna is struck, the lightning rod system will function in a normal manner, obviating the necessity for making a lightning rod system out of a radio antenna.

An inside antenna has the advantage that it does not represent an extension in space beyond that already taken by the house, and thus does not increase the likelihood of being struck. On the other hand, such an antenna is not protected from lightning appreciably, as some people suppose on account of the fact that the roof represents insulation, and if it were struck it would offer the same objections as the outdoor antenna. In addition, it would represent a greater fire hazard, because of its location inside. The same protective measures could be applied to the indoor antenna: a small gap to a good ground connection large enough so that it will

not be destroyed by the discharge. However, it is well to note that a vaporized antenna in an attic, as a result of a lightning stroke, is dangerous.

Many modern radios require no external antenna, and so eliminate any danger from lightning from this source. However, it is desirable to keep away from such a radio during a lightning storm for the same reason that makes it wise not to handle any electrical equipment any more than is necessary during lightning storms.

Checking a system of lightning protection, after changes have been made involving electric light wires or water or gas pipes which come within a few feet of lightning rod conductors, is always a good rule. The case mentioned in the last chapter of the properly installed lightning rod system which did not function correctly because of the light wires beneath the roof a few inches away is a good illustration.

The same rule applies if any changes in plumbing have caused the removal of ground connections for either telephone or power lines. The electric company and the telephone company should be informed of such changes for one's own protection.

Will tall trees near by protect a home? That depends upon local circumstances. Assuming that the tree is tall enough, and the house within its cone of protection, as a rule the tree will be struck in preference to the house, although there are many cases on record where such a

tree was not struck and the building was struck. What happens after that will depend upon several factors. If the tree is protected by a lightning rod system, the house will be protected also, if within the cone of protection. If the tree is not so protected, it may be blown apart, damaging the house. Or a side-flash might occur. Or if the grounds in the house, such as a water-pipe system, are good, a path may be plowed up in the earth between the base of the tree and the house. In each case, the damage resulting would obviously depend on the physical situation of various objects and structures.

Fire or explosion? The reasons why one or both of these effects are caused by a lightning stroke have been rather thoroughly covered in preceding pages. If a fire is caused, the object struck must have been inflammable and must have been held at a proper temperature long enough to cause ignition. Leaving explosive gases out of consideration, it can be repeated that long-continued lightning strokes, either of the multiple or of the continuing type or both, satisfy these conditions sufficiently to cause fire. Where high currents and short times of the order of millionths of seconds are involved, explosive action takes place which may be very violent. Strokes may persist for considerable periods of time, with superimposed high-current peaks, resulting in both explosive action and fire. In any case, this information can aid the reader only in telling him afterwards what

really happened, and it is academic rather than helpful.

Lightning does strike more than once in the same place, of course, and there is no foundation for the old adage other than casual observation unaccompanied by investigation. The mere fact that lightning has struck in a certain place is proof that it can strike there again, conditions being the same. Leaving out of consideration multiple strokes in which several discharges follow the same path in one stroke, objects which are quite directive, such as tall buildings, are struck repeatedly. As a rule, however, low objects such as homes are seldom struck more than once, because chance plays such a great part in determining the path of the discharge.

We have already touched upon the *mechanism of thunder,* and know that because of the passage of the current of the lightning stroke through the air, the air expands as it is heated. This wave of increased pressure reaches the human ear in the form of sound. When the current rises with extreme rapidity, as is frequently the case with lightning, the air also expands rapidly, giving rise to the sharp crack often heard when the stroke is near at hand. Remembering that strokes may consist of high-current peaks in rapid succession, in a time of a second or so, and that they may be a mile or more away and coupled with echoes coming from many reflecting surfaces, it is not difficult to understand the sound of thunder. It seems likely that cloud-to-cloud discharges

produce the rumbling type, while strokes to ground are likely to be sharp and of relatively short duration.

It is quite obvious that if the rate of current change in a lightning stroke is slow enough, very little sound will be heard of the type usually associated with lightning. Some strokes of this type have been observed. Available data seem to indicate that such strokes will be associated with tall structures rather than occurring in open country.

Steel-frame buildings are usually safe, as the steel is in contact with an extensive system of buried pipes, constituting a good ground. Within such a building there is little chance for appreciable differences of potential in case the building is struck, making such structures safe habitations in a storm. However, as we have seen, many such buildings are provided with stone or terra cotta parapets which the lightning may strike on its way to the steel, and the result is damage, with pieces of stone thrown to the street below. Such structures can easily be protected by arranging it so that lightning can easily get to ground directly without passing through non-conducting material.

The safety of the all-steel automobile in a thunderstorm was mentioned in connection with the Faraday cage. It is one of the best places to be in such circumstances, although changing a tire or filling the gasoline tank would expose one to danger. And if high-tension

wires should fall on the car, the occupants should remain inside until help comes, because stepping on the ground might be fatal.

Golf has been thought to be a dangerous pastime during a thunderstorm, but this is no reflection on the ancient game. It is the concentration of persons in the open which has led to this belief. The golf course is no more dangerous than the next field, and no more attractive to lightning. The use of metal clubs is of no consequence unless they are held above the head. If one were struck while holding a metal club, the burns from lightning would be concentrated, because of the better path represented by the metal of the club.

This is a good place to repeat the trite warning about standing under a tree, or overhead wires, transmission towers, or any other electrical apparatus. The tree, of course, acts as a good conductor during the first interval of the bolt, but is not able to carry large volumes of current. The discharge is liable to jump in any direction and not follow the tree to ground. Because of its height, a 60-foot tree is perhaps ten times more likely to be struck than a person standing in the open. That person may be hurt by flying branches, a side-flash from the trunk may strike him, or the potential may be too high for safety if the current is large enough and he is standing too close to the trunk. If the tree is protected by lightning rods, the first two sources of hazard are

eliminated, but the potential gradient will depend upon the system of grounds used, and where they are located with respect to the individual. It has been suggested that tree-protection along a principal thoroughfare should be provided, so that persons under the trees would be safer than in the open, since to take shelter under a tree seems to be a characteristic human tendency.

So much for some of the most insistent questions about lightning. The authors trust that the answers given will not only satisfy the reader's curiosity but will further justify their efforts by arming him against carelessness and neglect—two perils which pass Jove's famous bolt by a wide margin in creating suffering and disaster on the earth. The attempt has been made in these pages to do more than consider the freaks and surface manifestations, however, by exploring the mechanism of the lightning stroke and its pernicious effects upon the complex structure of modern life. In the course of this exploration we have described the battle that is being waged by the lightning-hunters along a wide front, first to understand the phenomenon, then to guard against it. As a result of their activity, we need no longer observe the flash and hear the roar from the mouths of our caves; we may step out boldly and do something about it.

It is only fitting to end this account with the same words which began it, for the benefit of those who seek

only a protective indifference to lightning, with a sound basis. Here they are, and may they add hours to your sleep:

If you heard the thunder, the lightning did not strike you. If you saw the lightning, it missed you; and if it did strike you, you would not have known it.

INDEX

Air-core delay cable, 143
Automatic reclosing, 34, 39

Ball lightning, 81, 82, 83
Berger, K., 97
Bismarck, Otto von, 11
Blue Hill Meteorological Observatory, 167
Bound charges, 124
Boys camera, 136, 137, 138, 141, 144, 158, 159
Boys, Sir Charles, 136, 138
Branching of lightning, 162, 163, 164
Braun, K. F., 69
Braun tube, 69, 70, 71, 72
Breaking-drop theory, *see* Simpson
British Institute of Civil Engineers, 45
Byrd Antarctic Expedition, 181

Calculograph, 146
Capacitor, 53, 55, 118
Cathode-ray oscillograph, *see* Oscillograph
Chesney, Cummings C., 21
Circuit breaker, 29, 30, 38, 39, 83
Cold lightning, 205
Cone of protection, 108, 109, 110, 165, 186, 207, 209, 222
Corona discharge, 29, 81
Counterpoise, 98, 101; continuous —, 98, 99; radial —, 99
Crater lamp oscillograph, *see* Oscillograph

Dufour, Alexander, 72, 73

Ediphone, 146
Edison, Thomas Alva, 12
Eiffel Tower, 73, 78
Elster, J., 173, 174, 175, 176
Empire State Building, 47, 121, 128, 129, 134, 137, 138, 139, 141, 142, 144, 149, 150, 151, 152, 158, 159, 164, 165, 166, 168, 176, 177, 201, 203

Encyclopædia Britannica, 182

Faccioli, Guiseppe, 21
Fechner, G. F., 11
Follow current, 38
Ford, Henry, 14
Fortescue, C. L., 94
Foust, C. M., 100, 109
Franklin, Benjamin, 8, 23, 24, 25, 32, 75, 78, 151, 200, 211
Fulgurite, 133, 134

Geitel, H., 173, 174, 175, 176
General Electric Co., 7, 52, 181, 206
Generator, 19, 20, 50, 51, 53, 54, 55, 65, 98, 103, 104, 106, 116, 117, 118, 119, 120
Ground fault, 30
Ground-fault neutralizer (Peterson Coil), 38, 40
Gulda, Alice, 167

Heat lightning, 213
Herkolite, 55
Humphreys, Dr. W. J., 82

Impulse generator, *see* Generator
Indirect stroke, 91, 93, 94, 95, 111
Induction, 90
Insulator, 27, 28, 29, 31, 36, 37, 41, 86, 97, 98, 101

Jacobs, Dr. Thornwell, 182
Jennings, W. N., 126, 168

Kelvin, Lord, 45, 64
Kenotron tube, 17, 49
Kite experiment (Franklin's), 25, 75, 78
Klydonograph, 76, 77, 78

Leader, 127, 128, 129, 130, 131, 132, 137, 160, 161, 162, 164, 189, 190
Leyden jar, 24, 49, 75, 78
Lewis, W. W., 100, 109
Lichtenberg, G. C., 75, 78
Lichtenberg figure, 75, 76, 77
Lightning arrester, 40, 41, 73
Lightning generator, *see* Generator
Lightning rod, 24, 25, 35, 37, 88, 183, 186, 194, 200, 201, 208
Lloyd, W. L., 138
Lodge, Sir Oliver, 108
Loomis, A. L., 138

Magnetic link, 99, 100, 101, 102, 191
Marx, E., 53, 54
McMorris, W. A., 138
Microphotometer, 147
Montgomery, 169
Multiple-aperture camera, 147, 148

Needle gap, 105
New York World's Fair, 54 *et seq.*
Nitrogen-fixation, 180
Norinder, Harald, 97

Oglethorpe University, 182
Oscillogram, 67, 73, 97, 98, 141, 150, 151, 155, 158, 159, 176
Oscillograph, 65, 66, 67, 68, 73, 74, 77, 79, 80, 84, 93, 96, 97, 98, 99, 102, 105, 131, 136, 141, 142, 143, 144, 148, 161, 163
Overhead ground wire, 35, 36, 37, 40, 98
Ozone, 56

Peek, Frank W., Jr., 21, 22, 52, 53, 94, 104, 107, 108, 109, 110, 211
Peters, J. F., 76
Peterson Coil, *see* Ground-fault neutralizer
Pittsfield Lightning Observatory, 153 *et seq.*, 168
Pressure wave, 112 *et seq.*, 156
Pre-stroke condition, 125
Protective devices, 33 *et seq.*
Protective masts, 40
Protector tube, 37, 38, 40, 86
Pyranol, 55

Reflection, 85, 86, 87, 88
Remscheid, Emil, 15, 16
Rod gap, 105

St. Elmo's fire, 125
Schonland, Dr. B. F. J., 96, 127, 128, 129, 130, 136, 137
Simpson, Sir George, 172, 173, 176
Sphere gap, 104, 105, 106
Steinmetz, Charles Proteus, "The Thunderer," 8, 11, 13, 14, 16, 17, 19, 20, 21, 23, 45, 47, 50, 52, 65, 114, 211
Streamer, 127, 130, 147, 162, 163, 166, 167, 189, 190
Surge-crest ammeter, 100
Surge-voltage recorder, 78

Thunder, cause of, 156, 223
Thyrite, 142
Torok, J. J., 95
Transmission line, 26-27, 28, 29, 30, 31, 33, 35, 39, 91, 92, 94, 95, 100-101, 132, 143, 178
Transformer, 46, 53, 59, 83, 84, 88, 197
Traveling wave, 31, 83, 84, 85, 86, 87, 88, 89, 93, 98
Trowvelot, 75

U. S. Census Bureau, 202
U. S. Superintendent of Documents, 208
U. S. Weather Bureau, 82
University of Breslau, 11

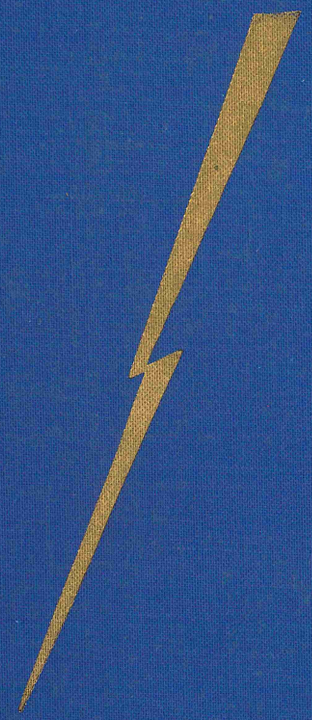
Wade, E. J., 73
Wells, H. G., 55, 104
Whitney, Willis R., 12
Wilson, C. T. R., 174, 175, 176

Zurich Polytechnical School, 12

C

McEACHRON

PATRICK

PLAYING WITH LIGHTNING

RANDOM HOUSE